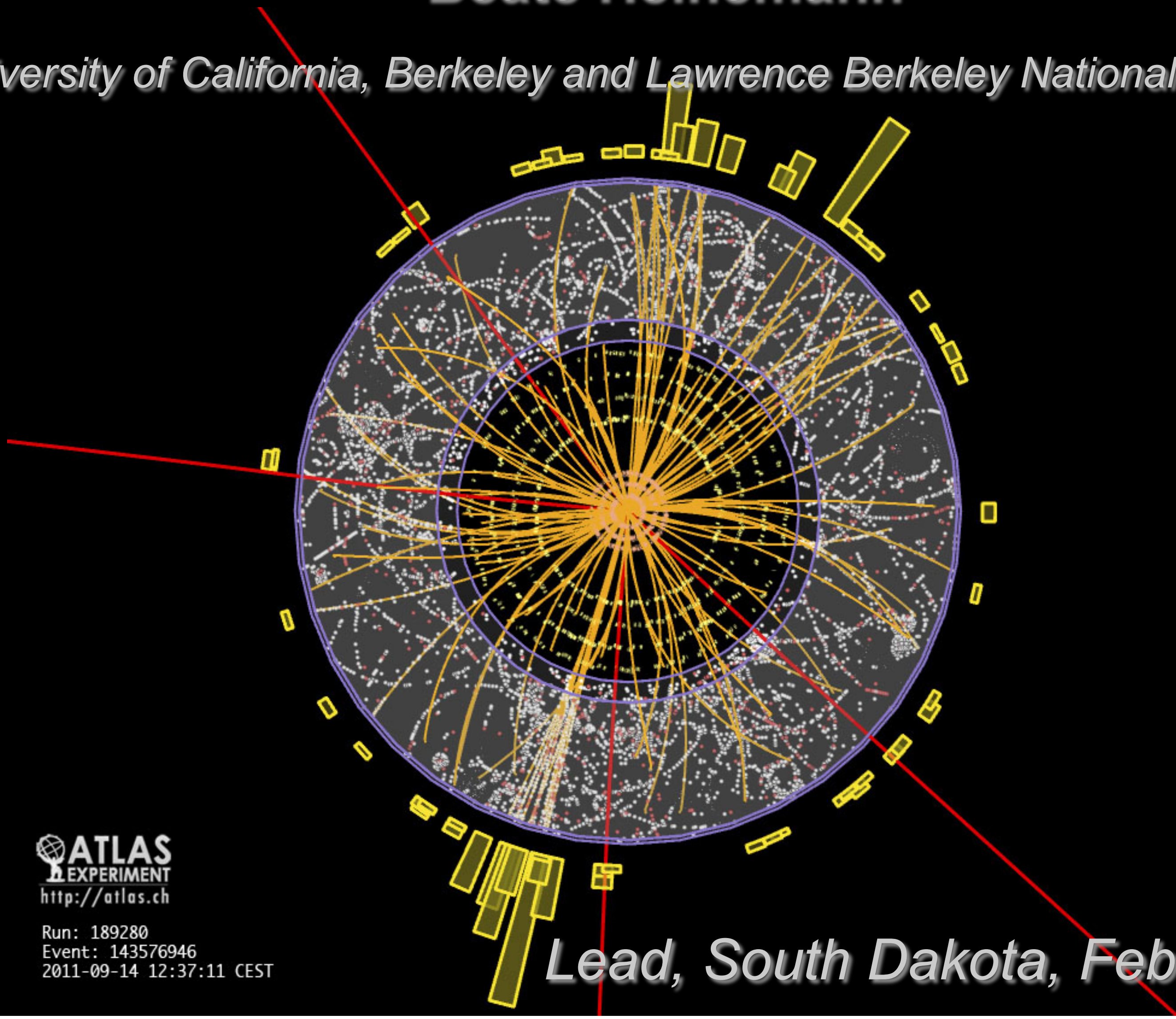
Observation of a Higgs-like Boson at the Large Hadron Collider

Beate Heinemann

University of California, Berkeley and Lawrence Berkeley National Laboratory

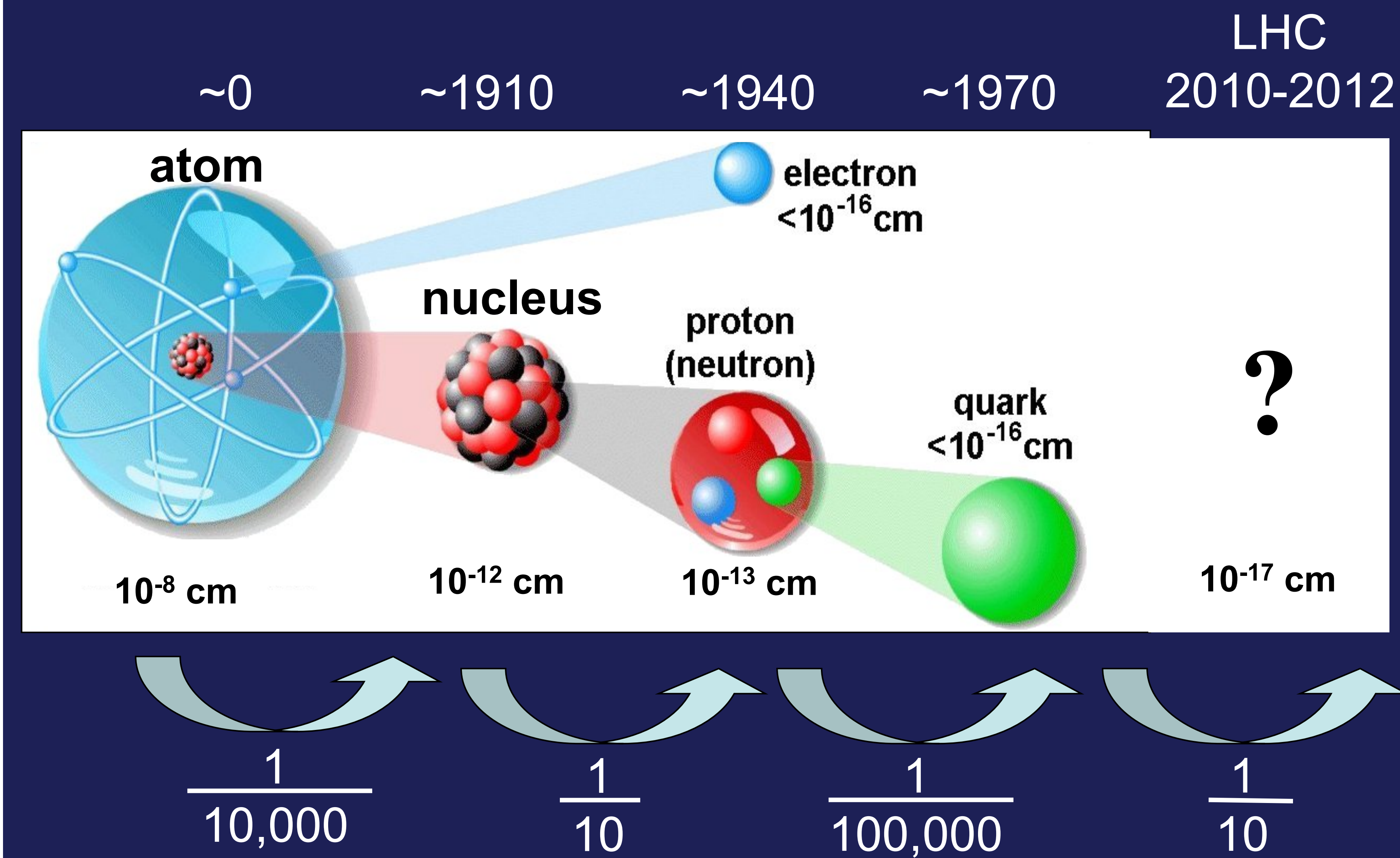


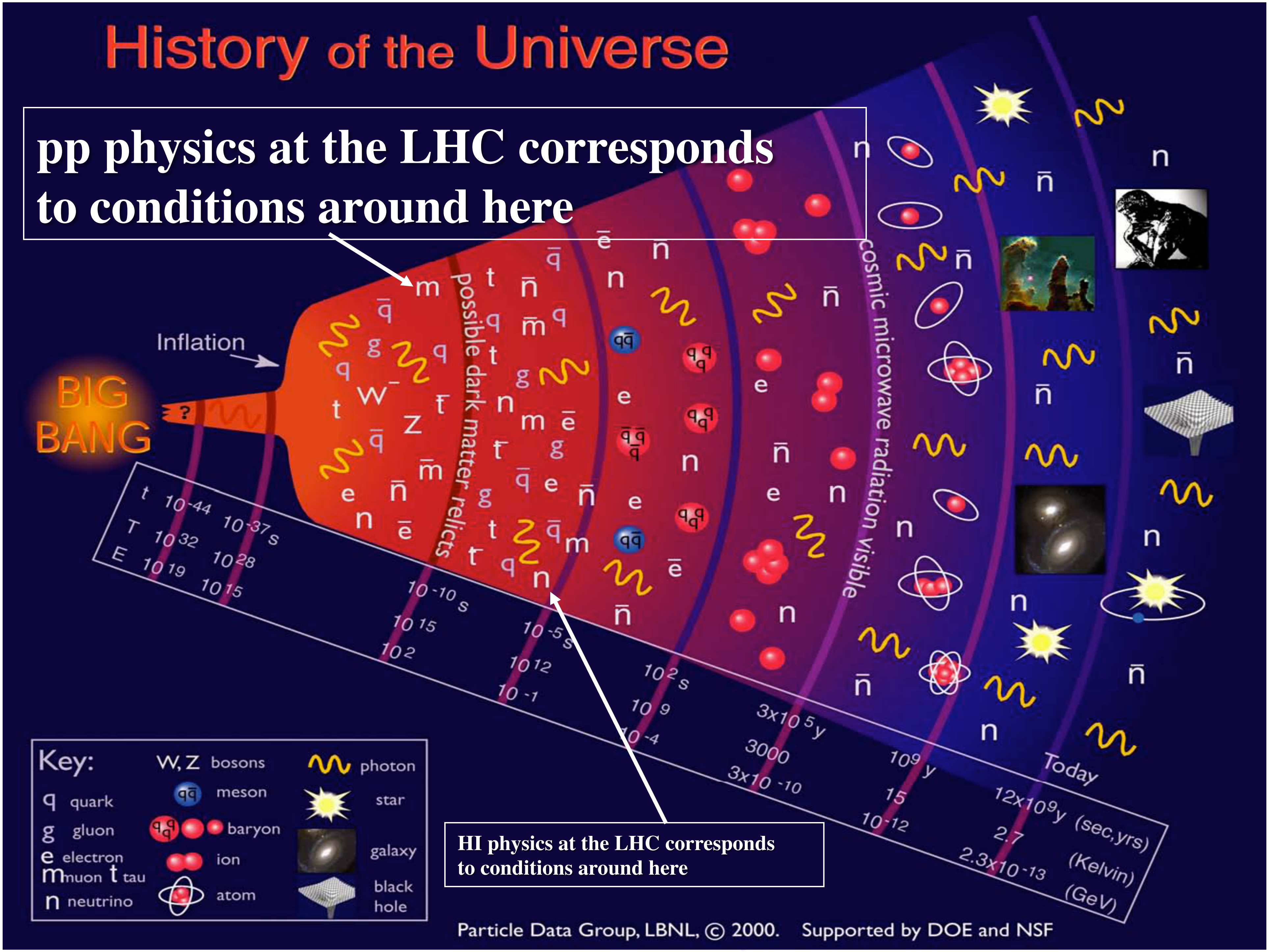
Lead, South Dakota, February 2013

Outline

- Particle Physics and the role of the Higgs Boson
- The LHC and the ATLAS and CMS Detectors
- The Search for the Higgs Boson
- Conclusions and Outlook

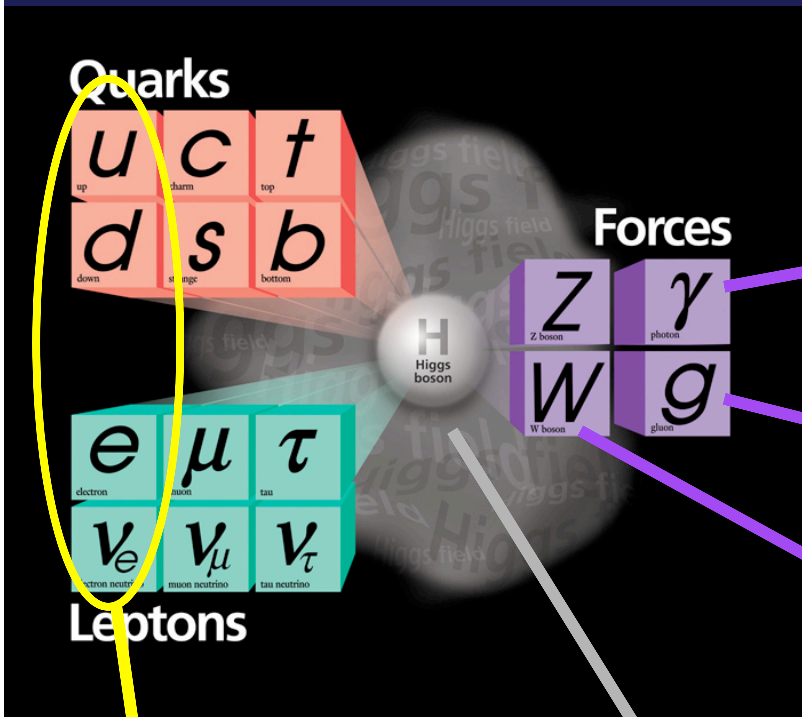
In Search for Fundamental Particles

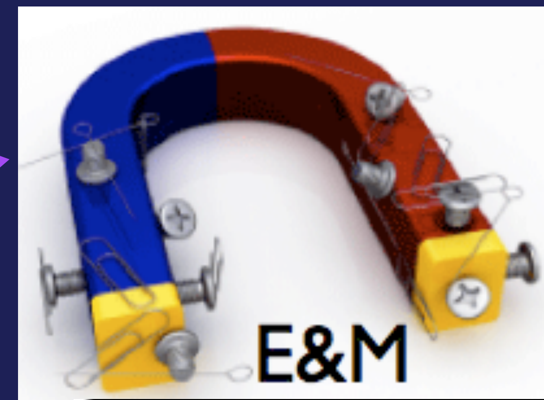


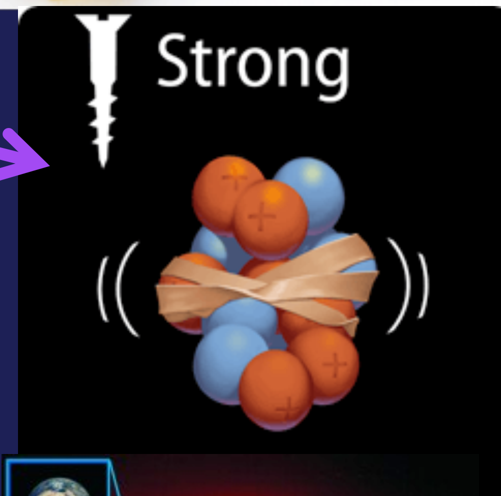

History of the Universe
pp physics at the LHC corresponds to conditions around here
HI physics at the LHC corresponds to conditions around here
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

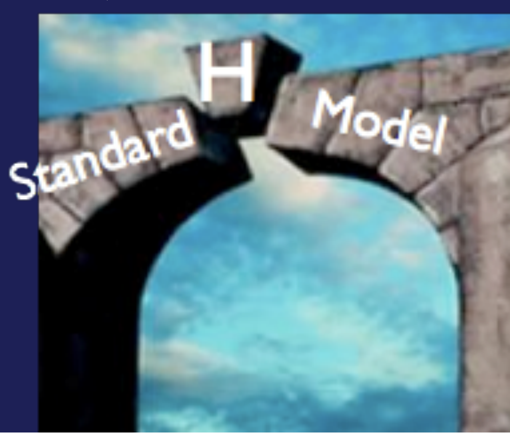
Road Map

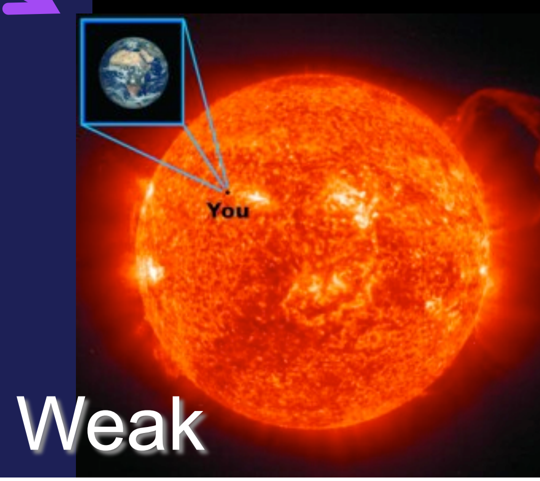
What do We Know?



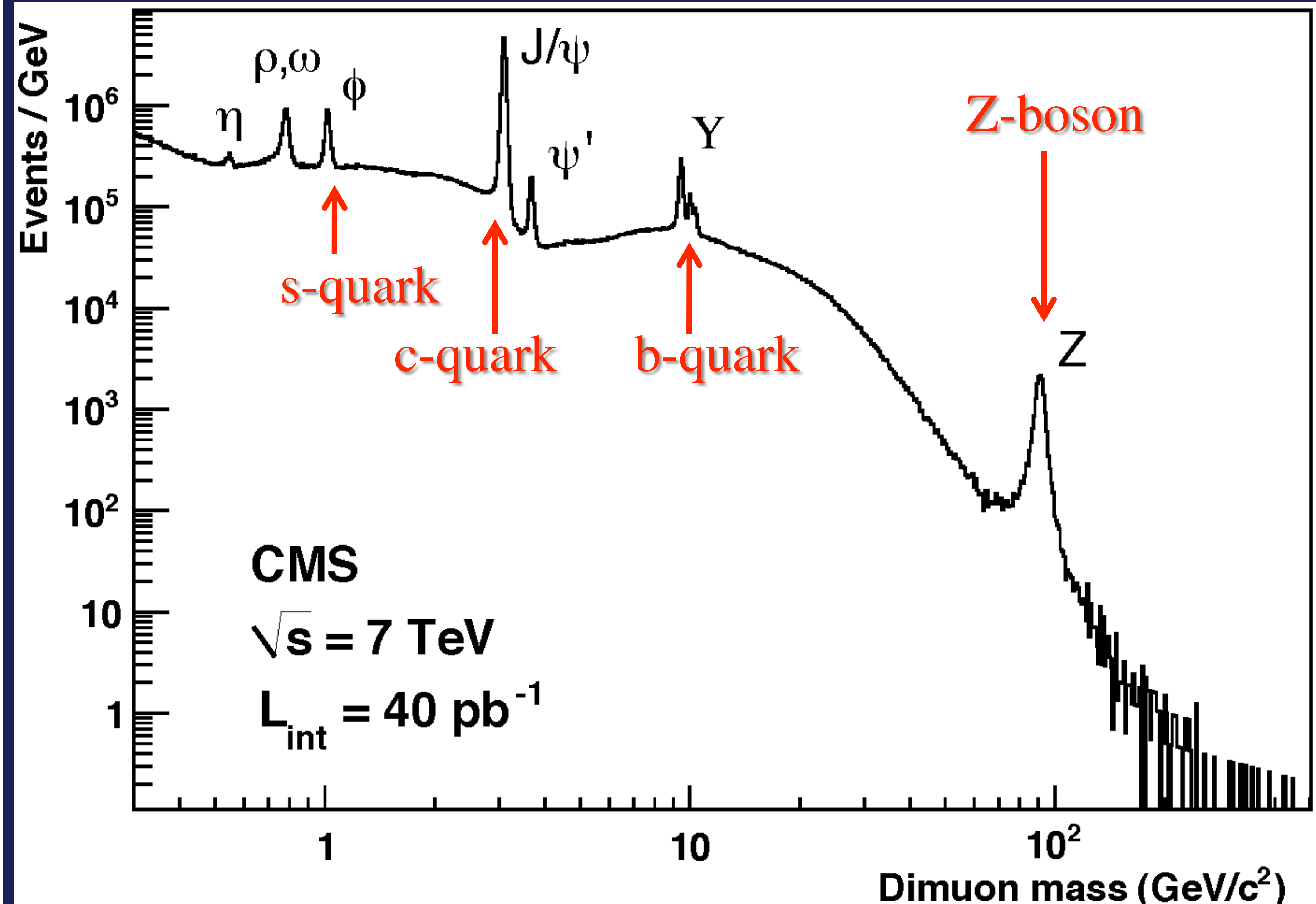




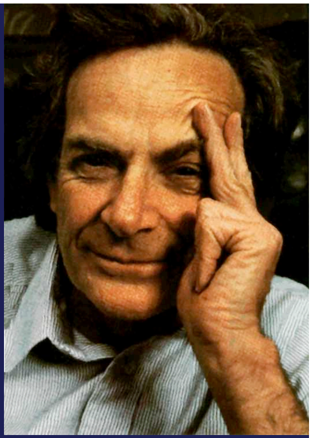




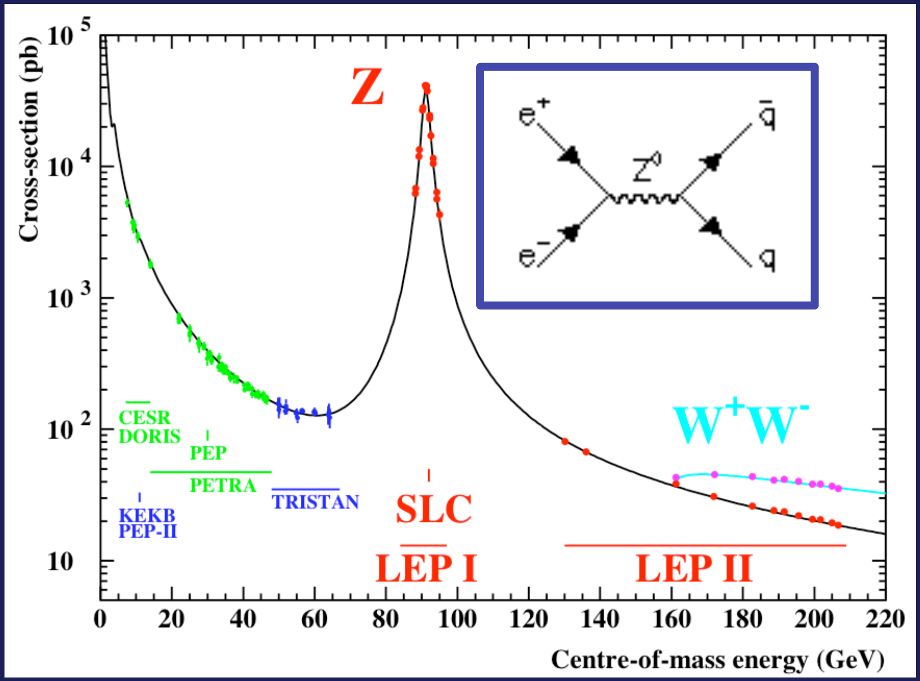
Dimuon Mass Spectrum

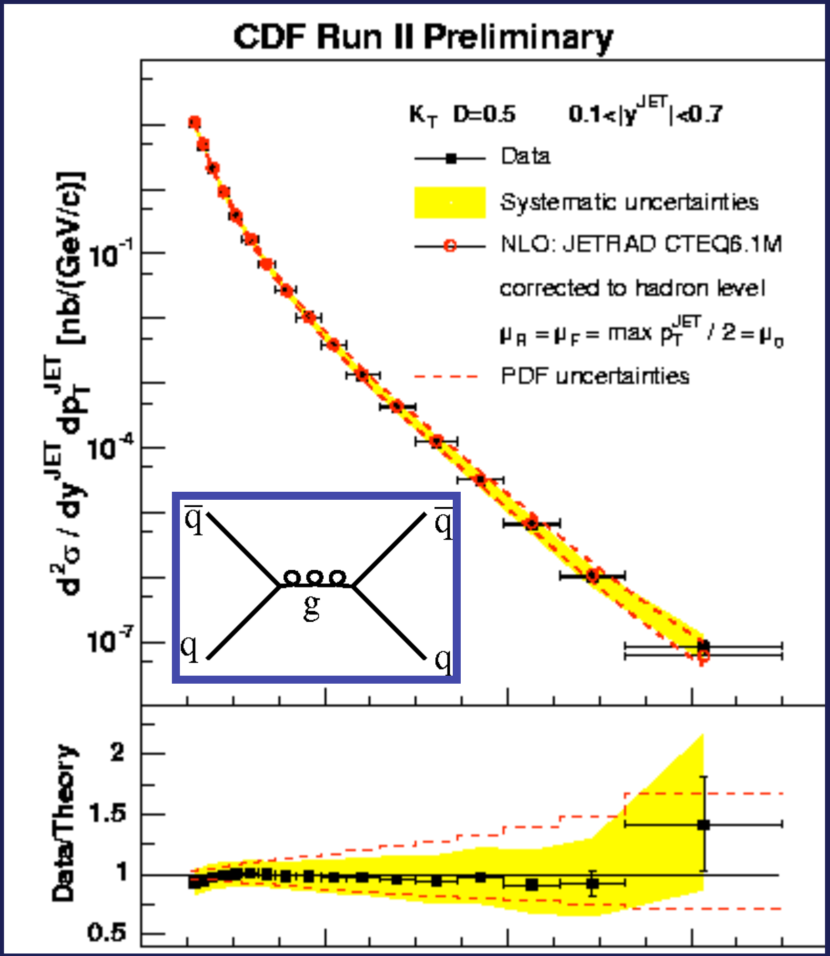


The "Standard Model": the most precise theory there is!



- "Feynman diagrams" allow us to calculate any processes with precision better than 1-10%





Tested in many experiments since 1960s

The Standard Model Formula

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\,\bar{\psi}D\psi$$

gauge sector

$$+\,\psi_i\lambda_{ij}\psi_j h + \text{h.c.}$$

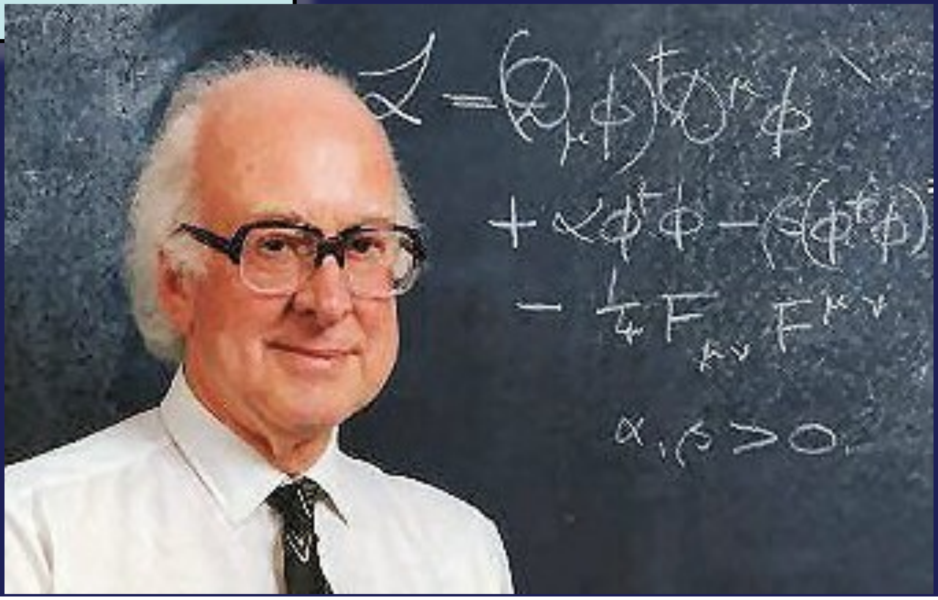
flavour sector

$$+\,|D_\mu h|^2 - V(h)$$

Higgs sector

$$+\,\frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

ν mass sector



Why Do Particles Have Mass?

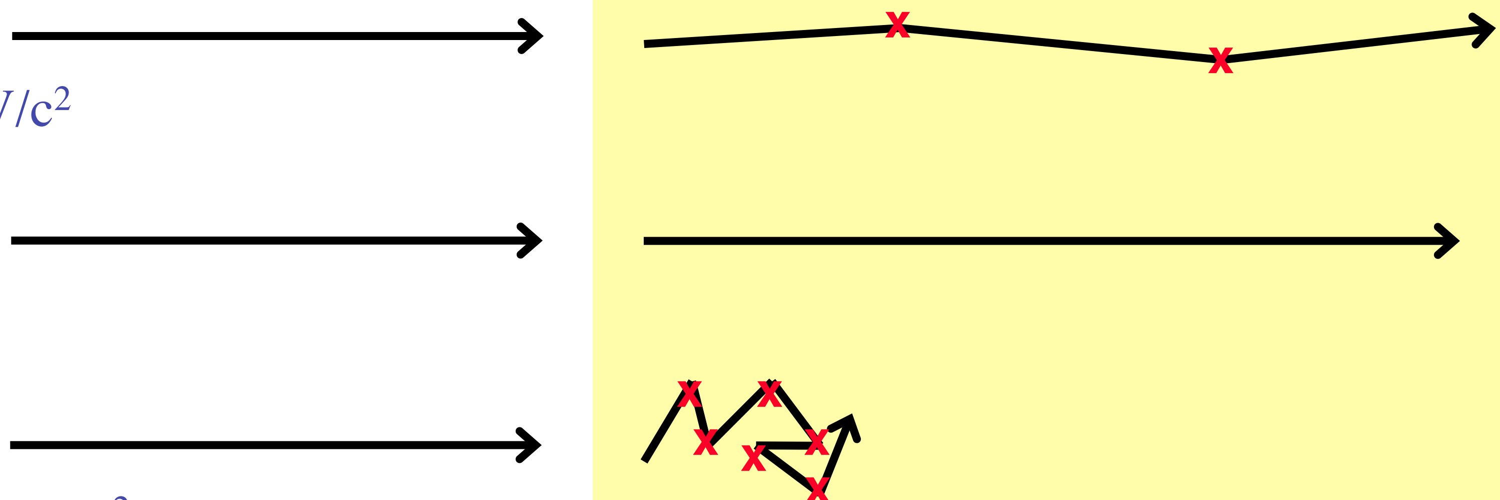
Nothing in the universe

Higgs field in the universe

Electron
m=0.511 MeV/c^2

Photon
m=0

Top Quark
M~172000 MeV/c^2



- Higgs field
  - – is present everywhere
  - – slows heavy particles down ⇔ gives them mass

How the Higgs Field gives Mass

Cocktail party:
Guests are evenly spread

Arrival of celebrity:
Guests cluster near celebrity

D. Miller / UCL

Celebrity moves more slowly <=> acquires mass (guests act like Higgs field)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

… a lot happened …

by the mid 90's the Higgs boson was considered the most critical particle to be found experimentally

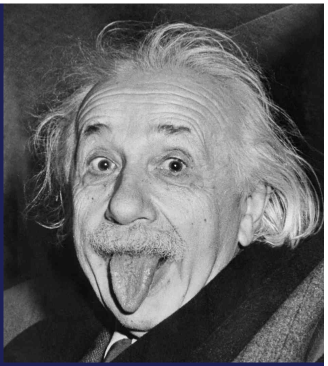
LHC and the
ATLAS and CMS Detectors

Units and Numbers

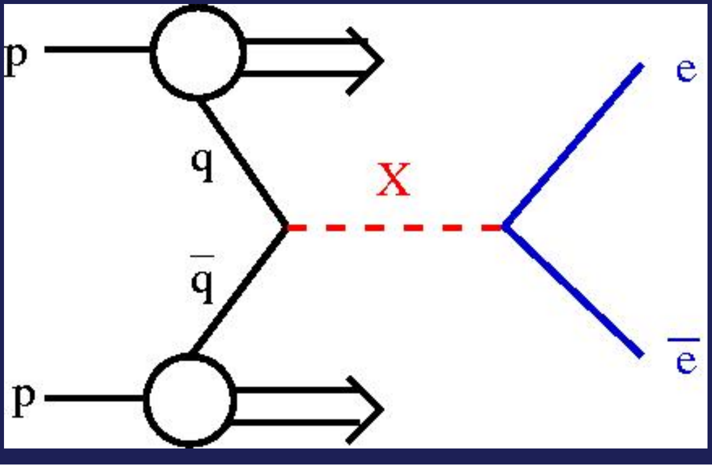
- Energy is measured in electron volts (eV):
  - *the amount of kinetic energy gained by a single unbound electron when it accelerates through an electrostatic potential difference of one volt.*
- *For example:*
  - *1 eV = $1.60217653(14)\times10^{-19}$ joules*
  - *electron mass = $.511 \times 10^6$ eV/c^2*
  - *proton mass ≈ 10^9 eV/c^2 = 1 GeV/c^2 ("Giga electron volt")*
  - *Z boson mass = 91 GeV/c^2*
  - *top quark mass=172 GeV/c^2 (≈mass of gold atom)*

TeV = "Tera electron volt"
= 10^{12} eV ≈ 1000 x proton mass / c^2

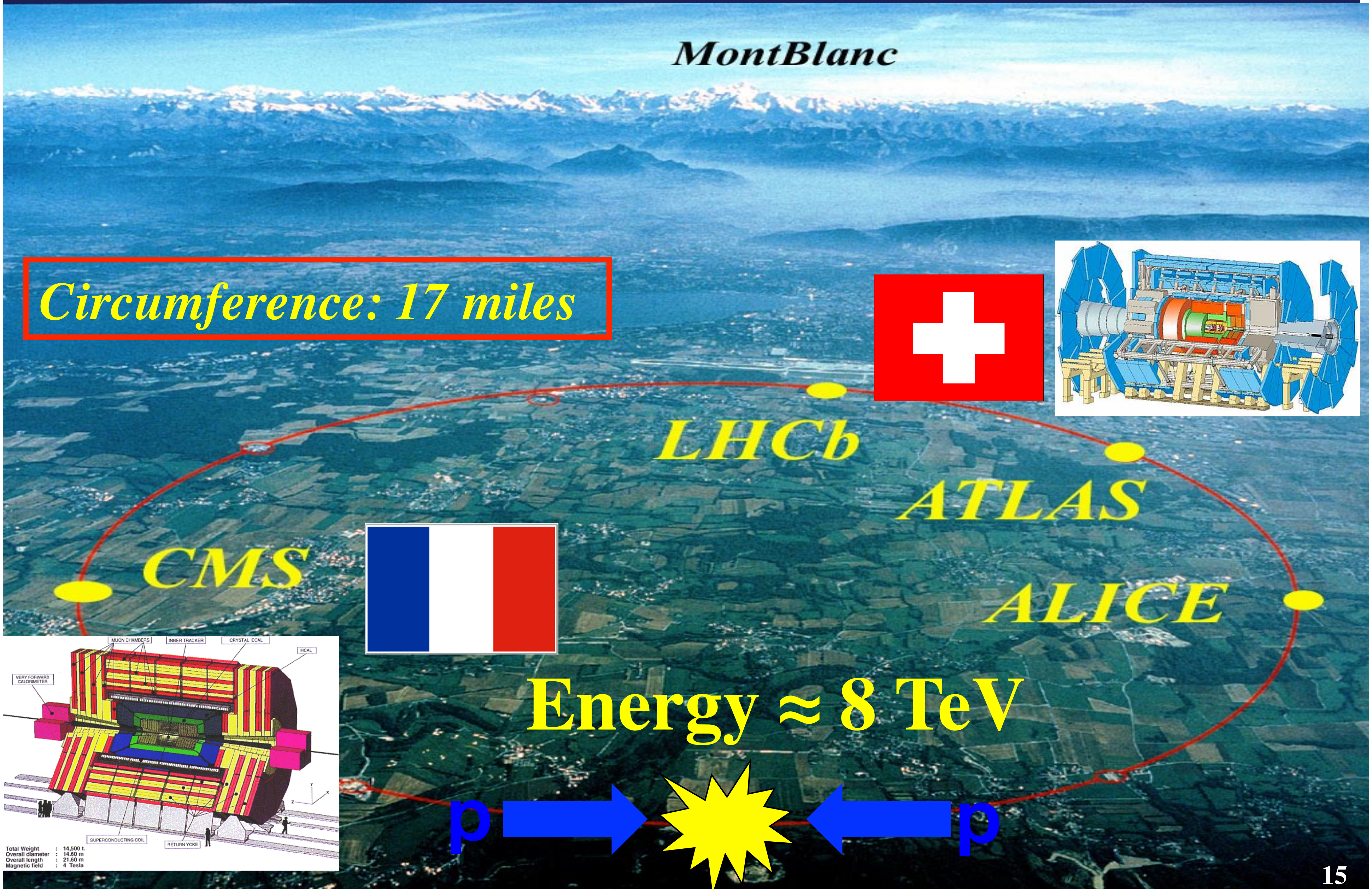
General Concept: $E=mc^2$



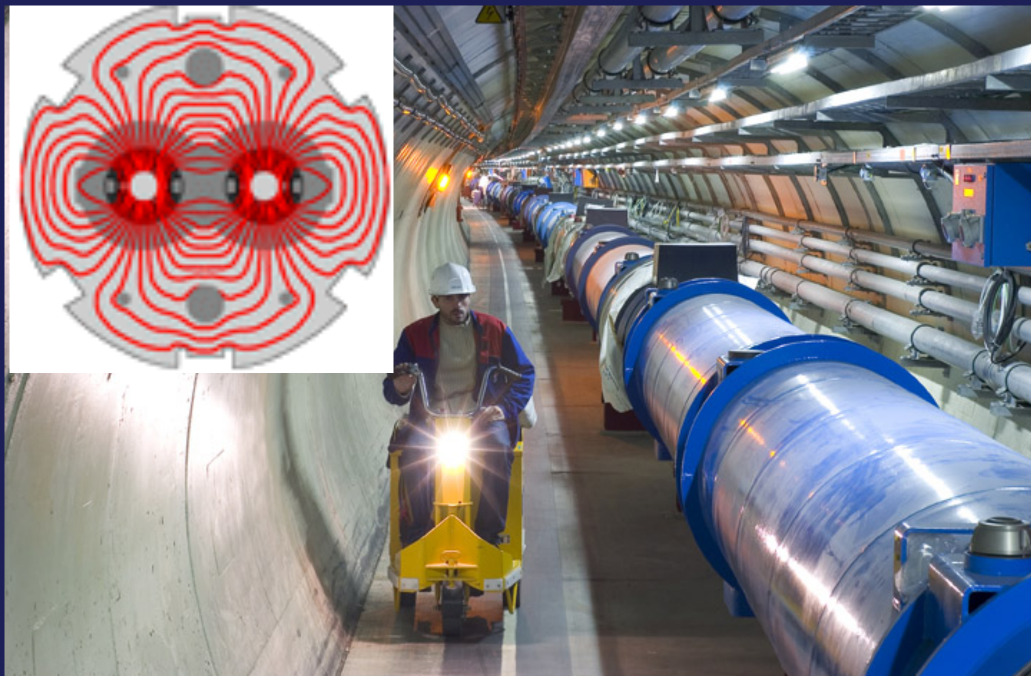
- Energy and mass are equivalent
  - $E=mc^2$
    - c = speed of light, m = particle mass, E = particle energy
- Collide 2 protons with E=4 TeV each
  - Total energy: 8 TeV
  - Can create particle X with mass $\mathbf{m_X < 8\ TeV \times c^2}$
    - Actual interactions occur between quarks and gluons that carry part of proton energy
    - Most particles we create live only for a very short fraction of a second and then decay



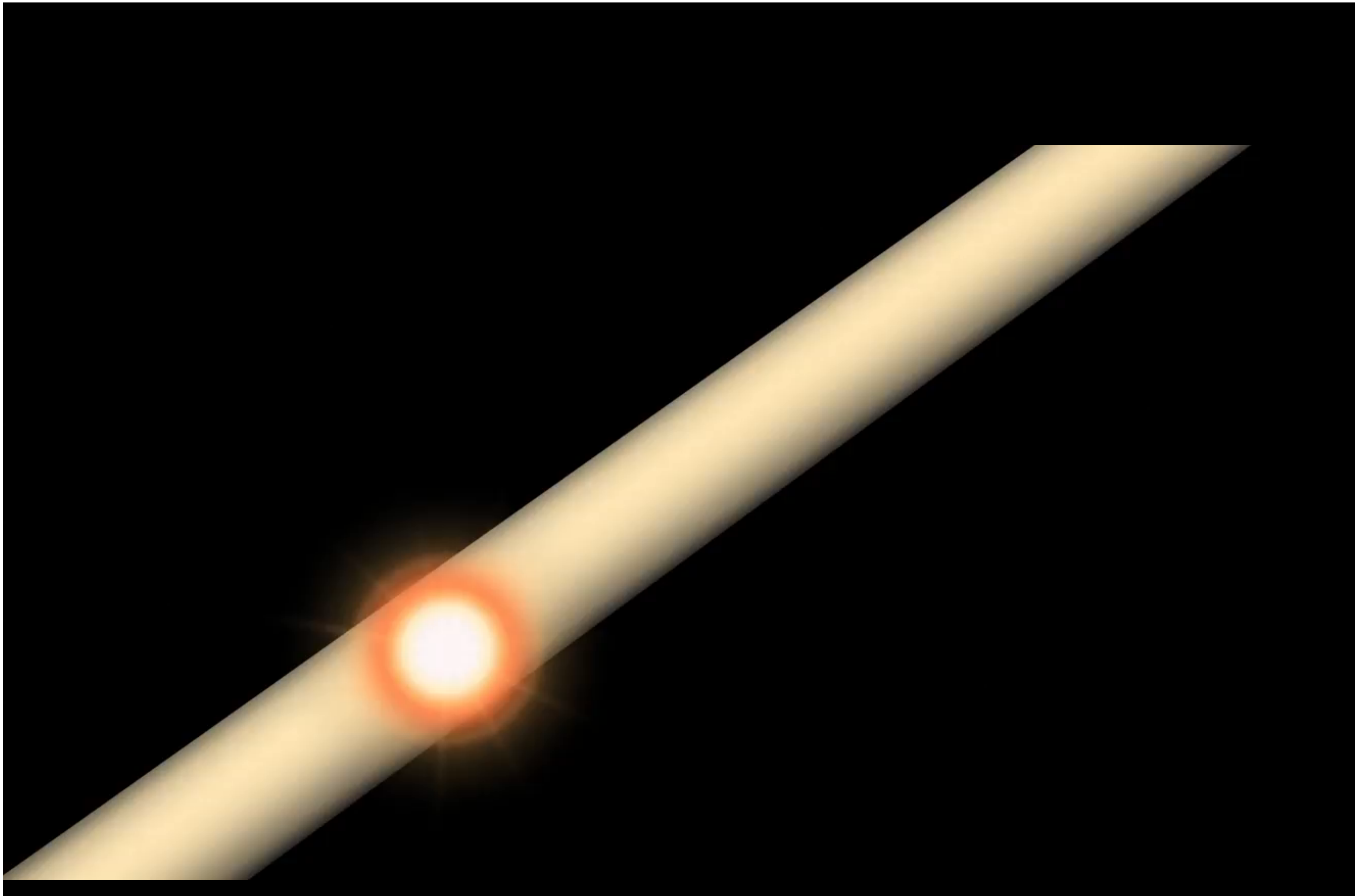
The Large Hadron Collider (LHC)



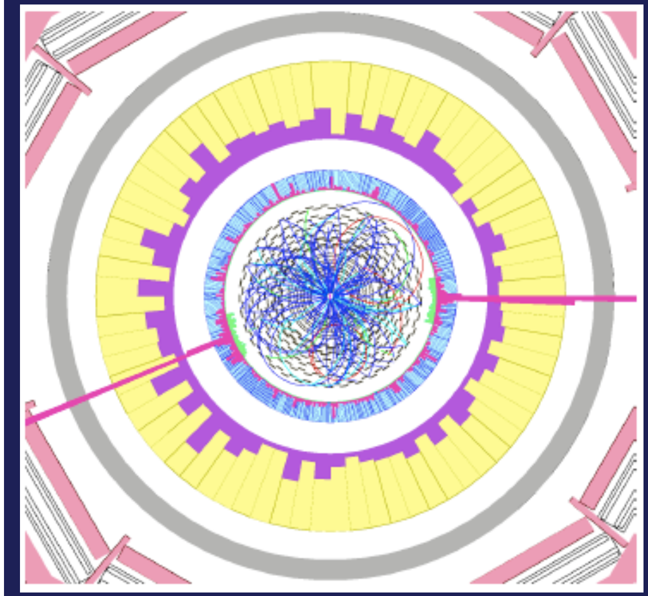
LHC Accelerator



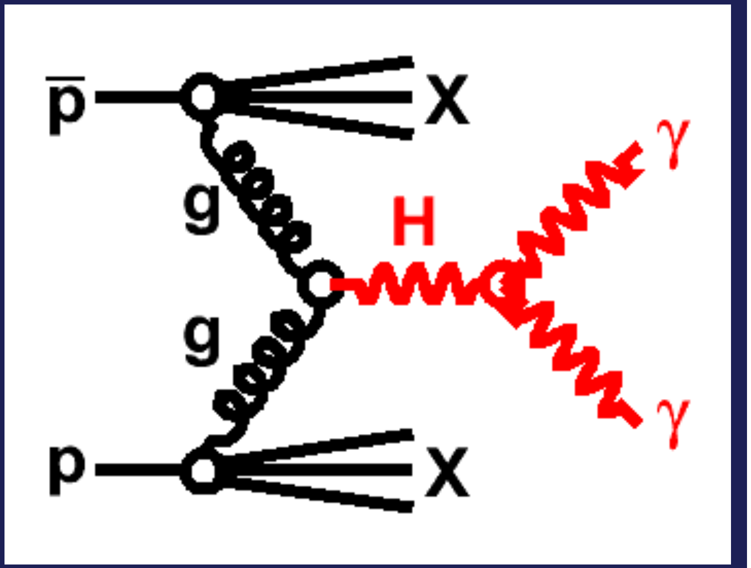
- About 300 ft under ground
- 9,600 superconducting magnets cooled to 1.9K (≈ -271 C)
- Dipole magnets operate at a field of up to 8 Tesla



How to detect the Higgs Boson

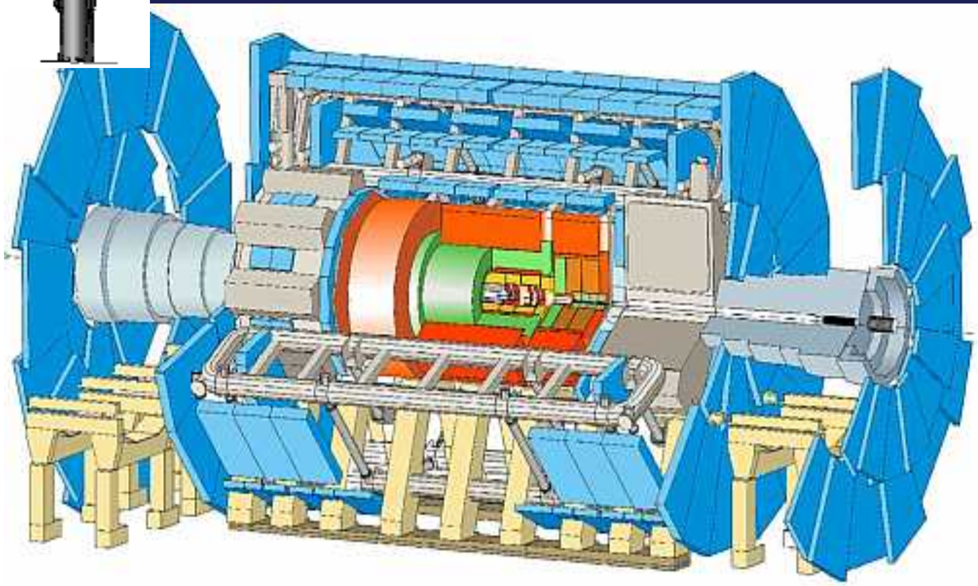


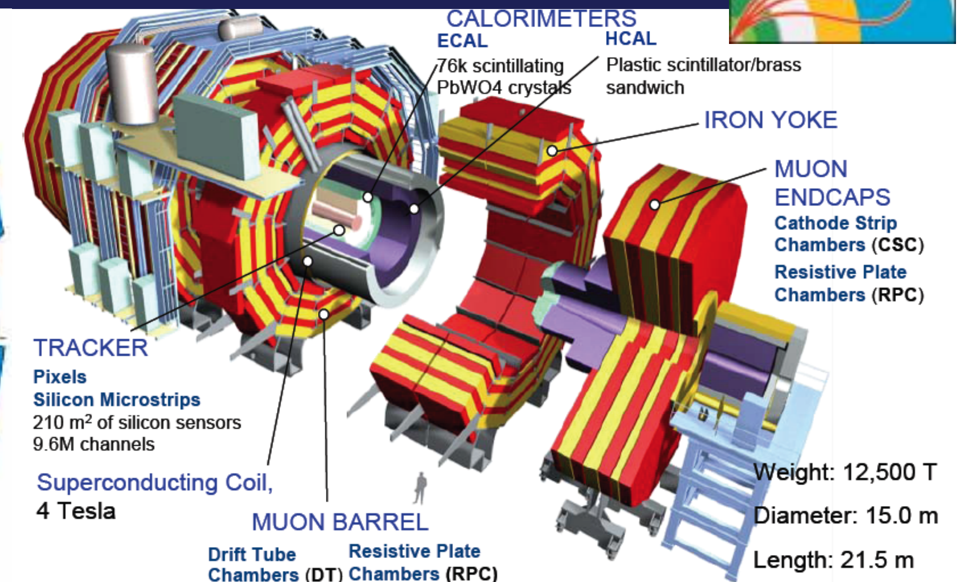
Higgs ?



- Measured hits in large detectors
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

ATLAS and CMS Detectors





	Weight (tons)	Length (ft)	Height (ft)
ATLAS	7,000	140	80
CMS	12,500	70	50

Detector Size in Perspective

Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

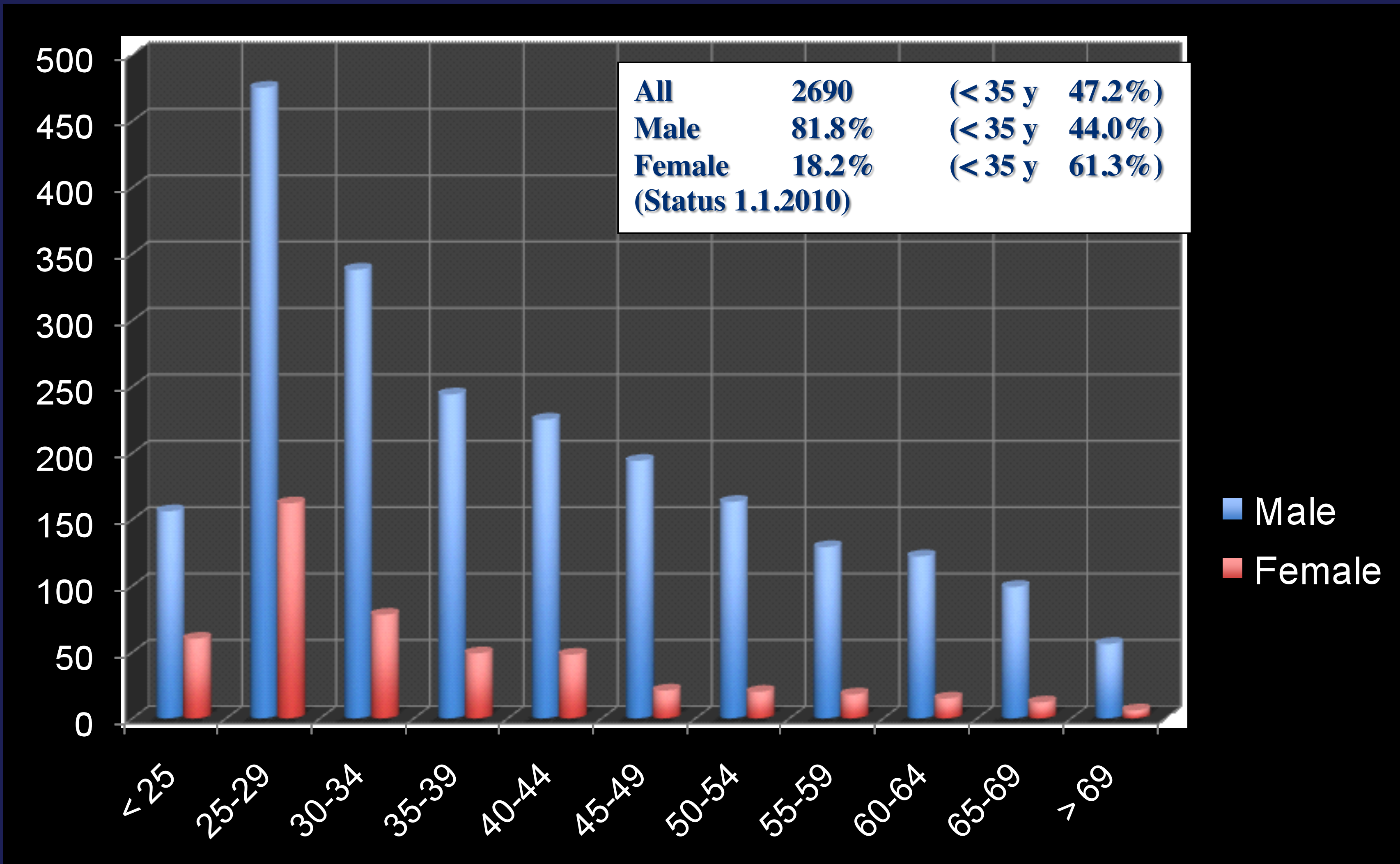
ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

founded in 1992

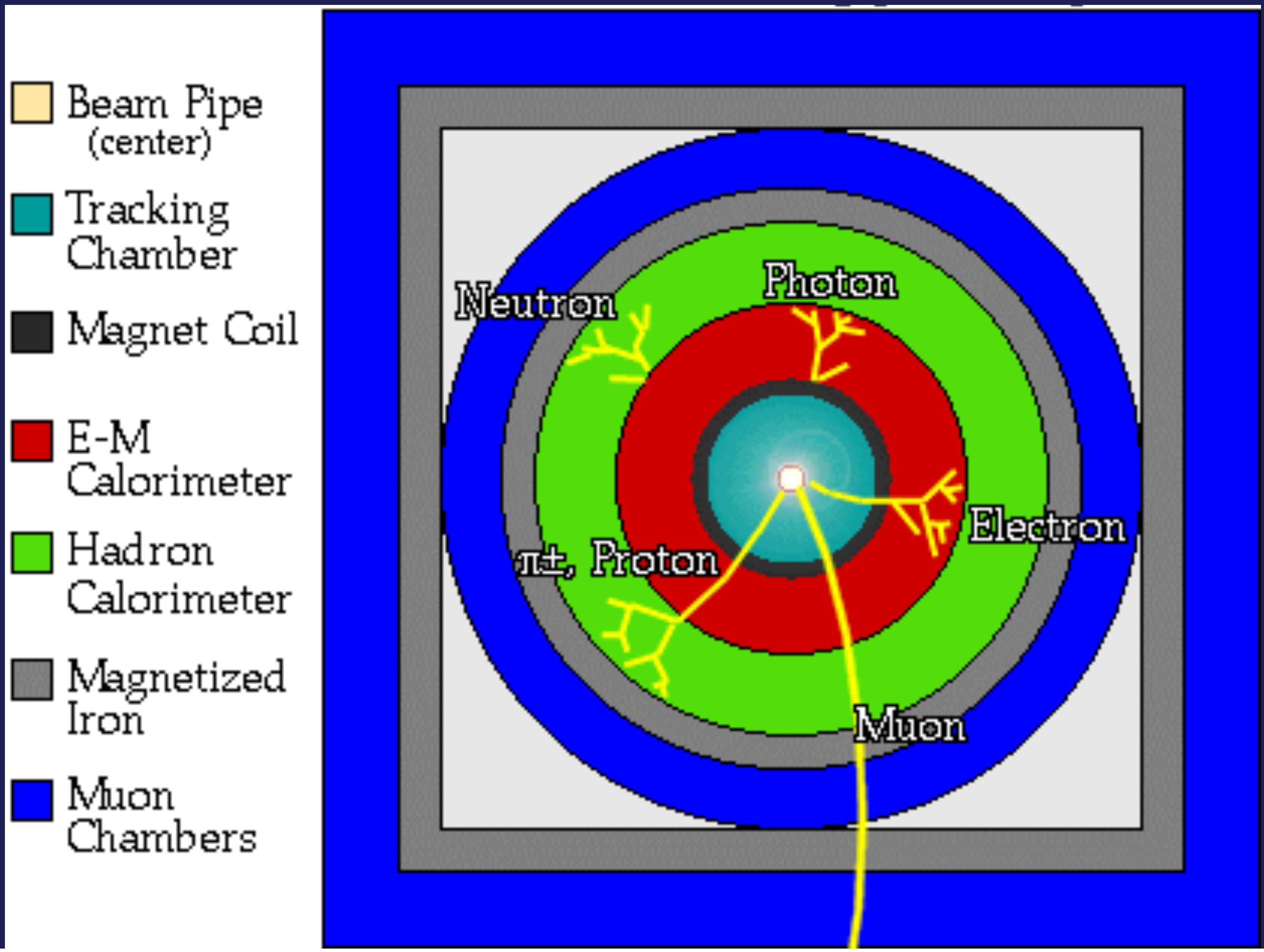
Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

Age and Gender Profile of ATLAS



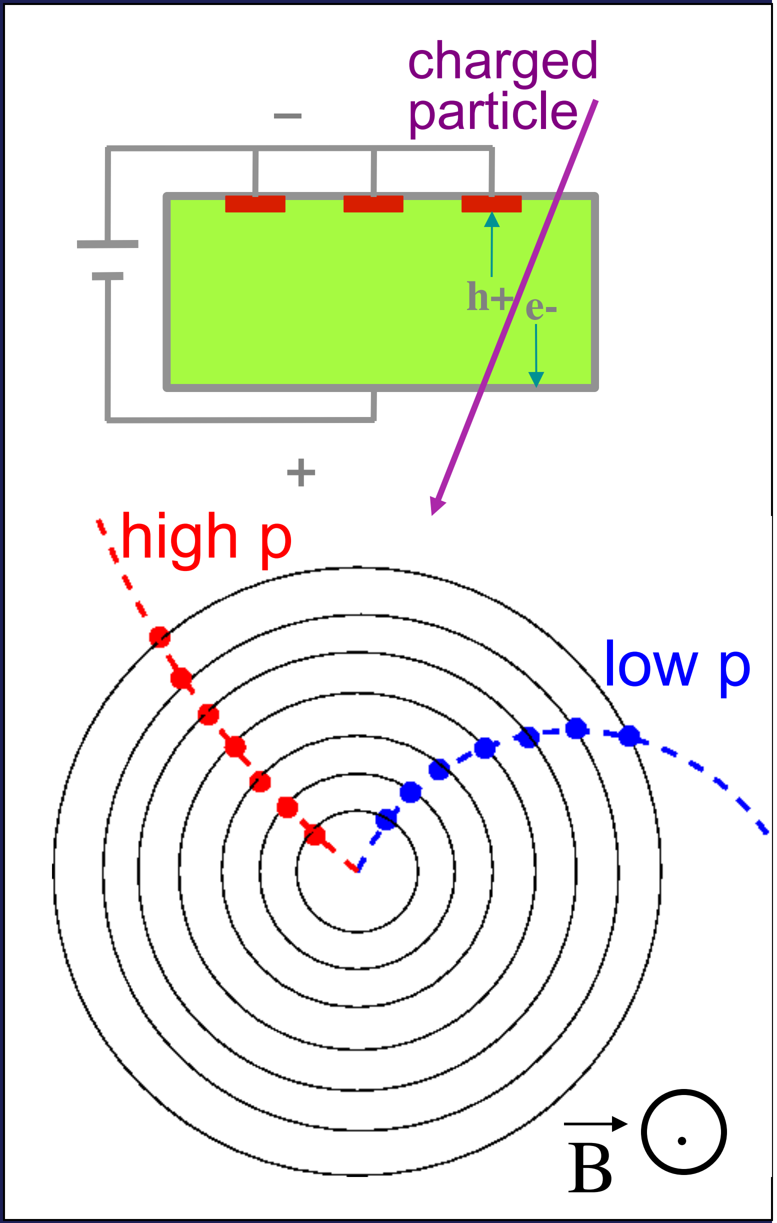
Particle Identification

- Collisions enclosed by layers of different detectors:
  - separate particle types
  - measure their energies and angles

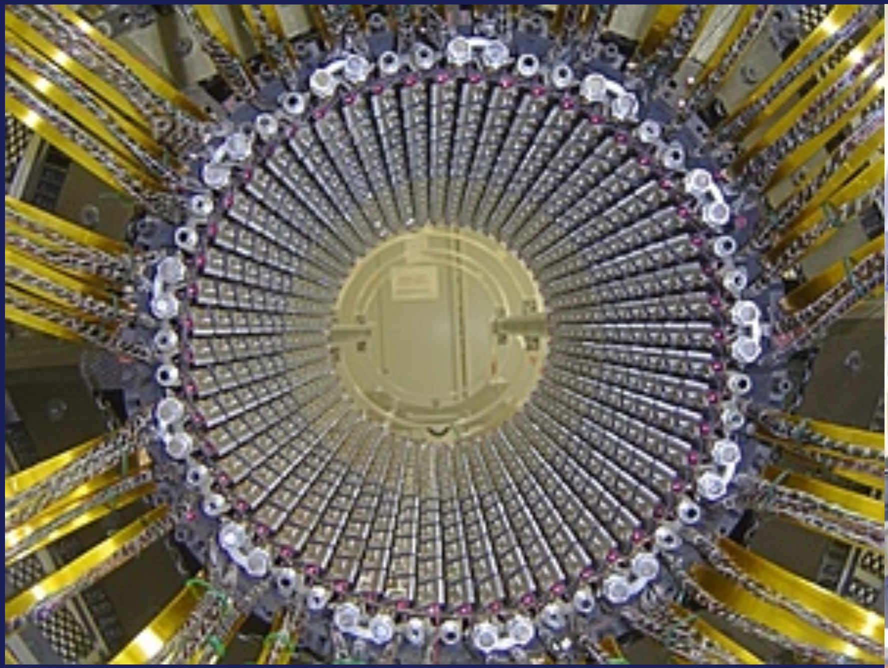


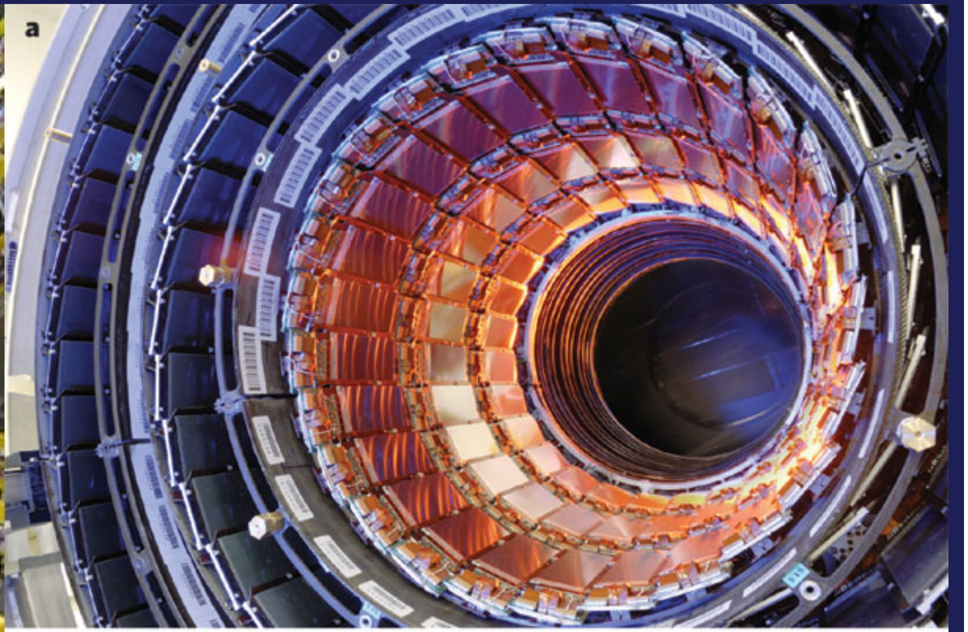
Charged Particle Tracking Detectors

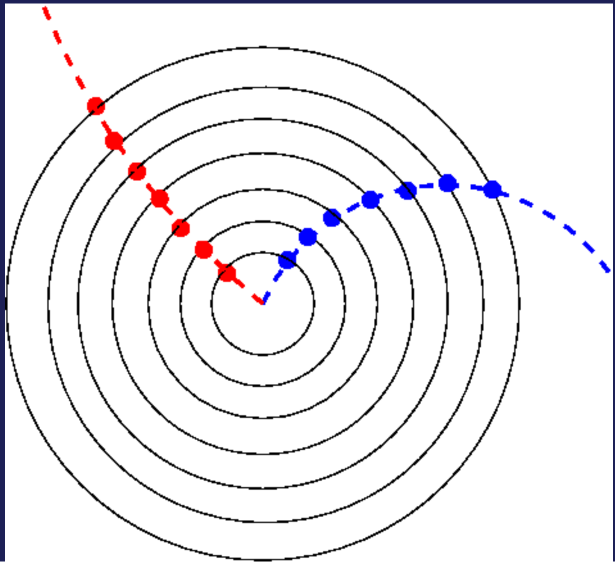
- Charged particle traverses gas or silicon
  - Sets free electrons
    - Measured charge gets collected at electrodes
  - Thus we find out position of particle
    - Resolution typically 15 μm
- Detector placed inside magnetic field:
  - Lorentz force: $\mathbf{F}_L \sim q\ \mathbf{v} \times \mathbf{B}$
- Hits along trajectory are fit to form a track
  - deviation from straight line proportional to momentum (**p~v**)
  - Direction of curvature tells us the electric charge

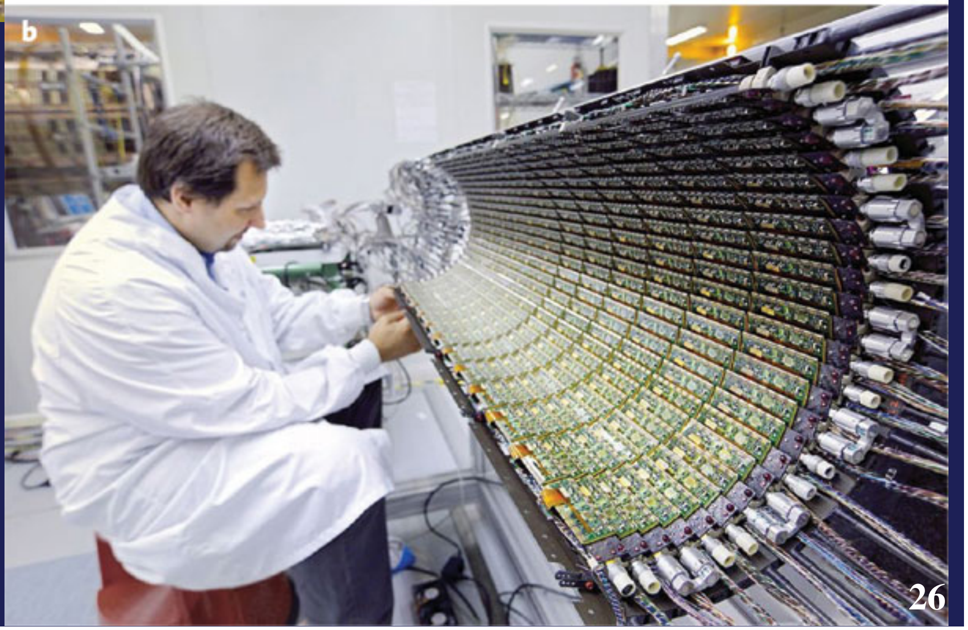


Tracking Detectors

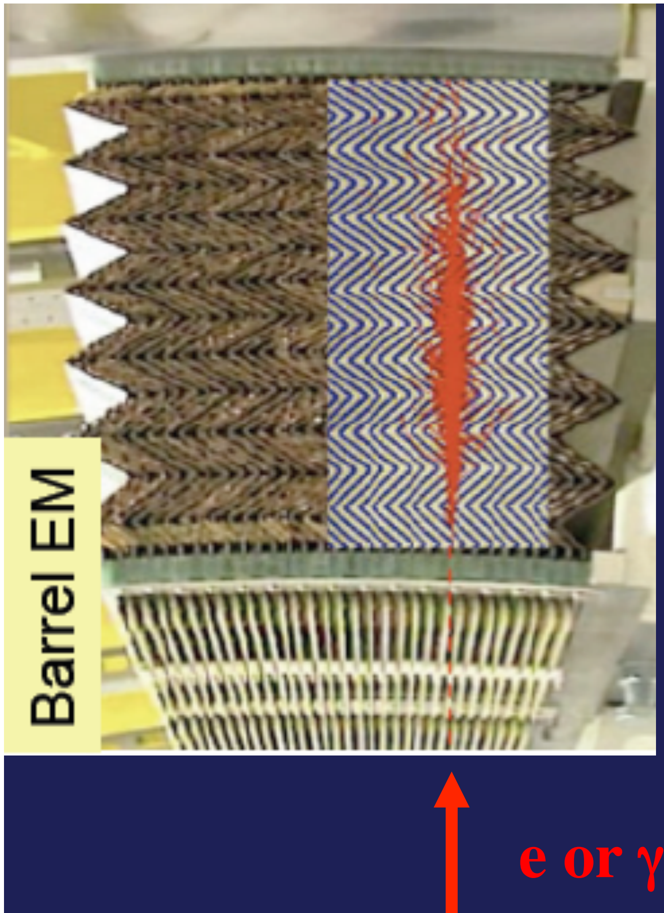




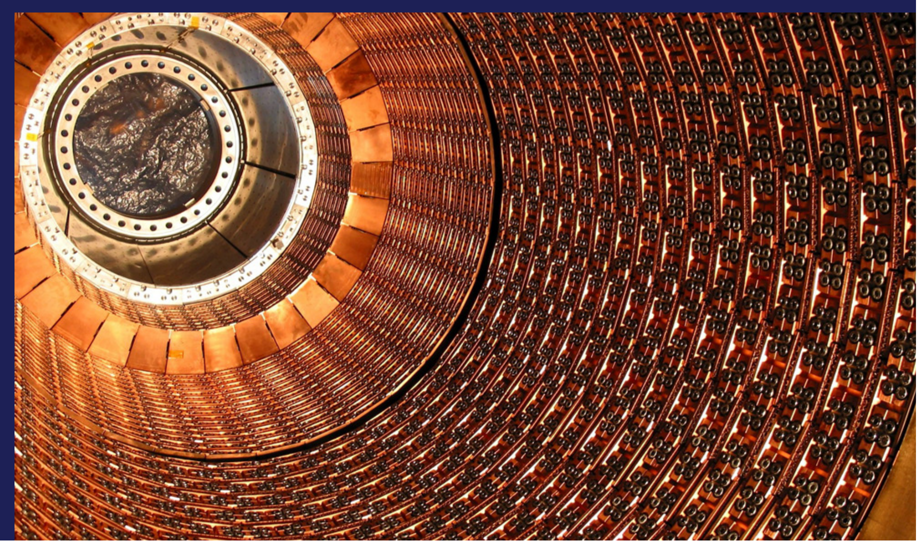


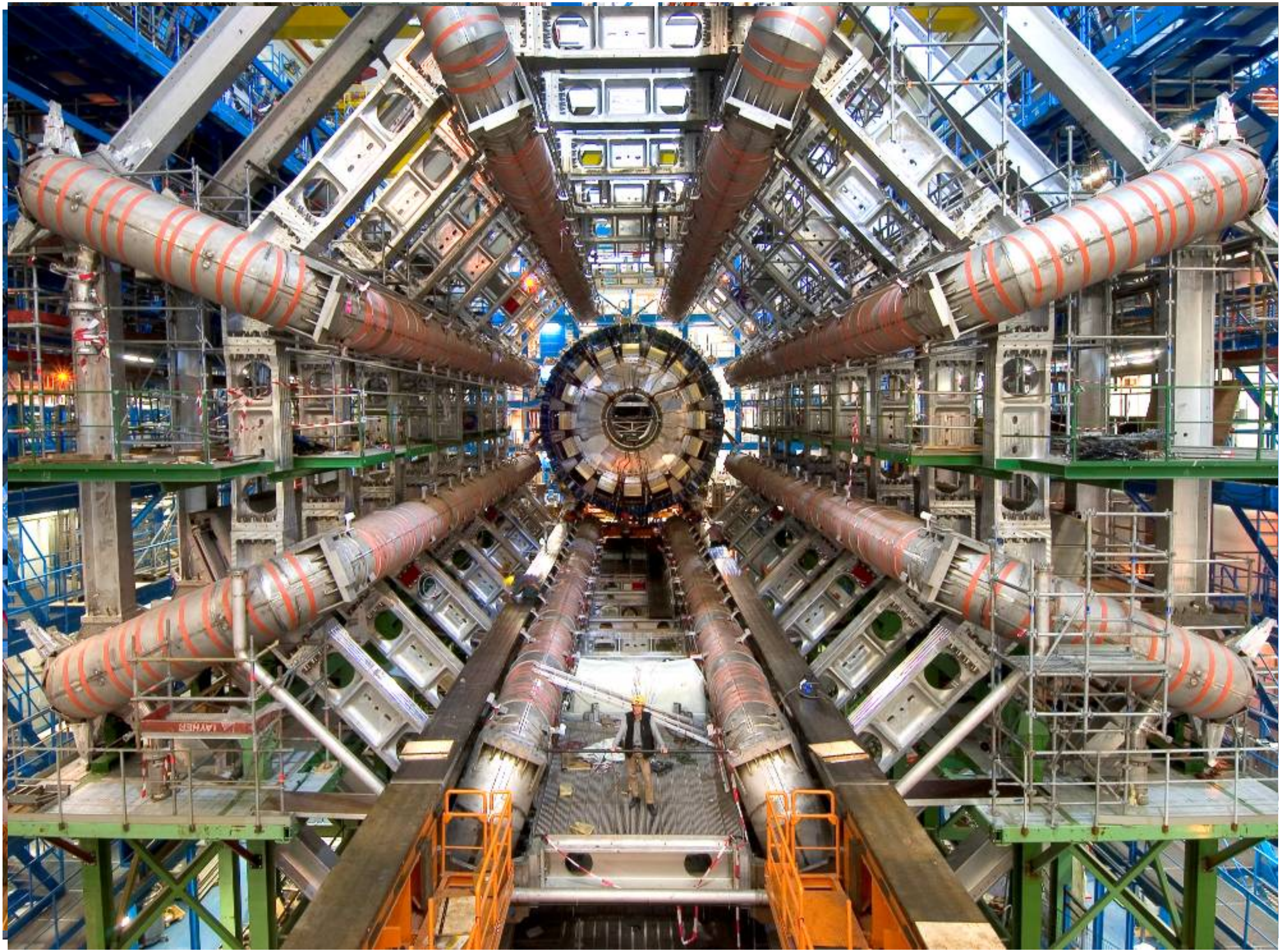


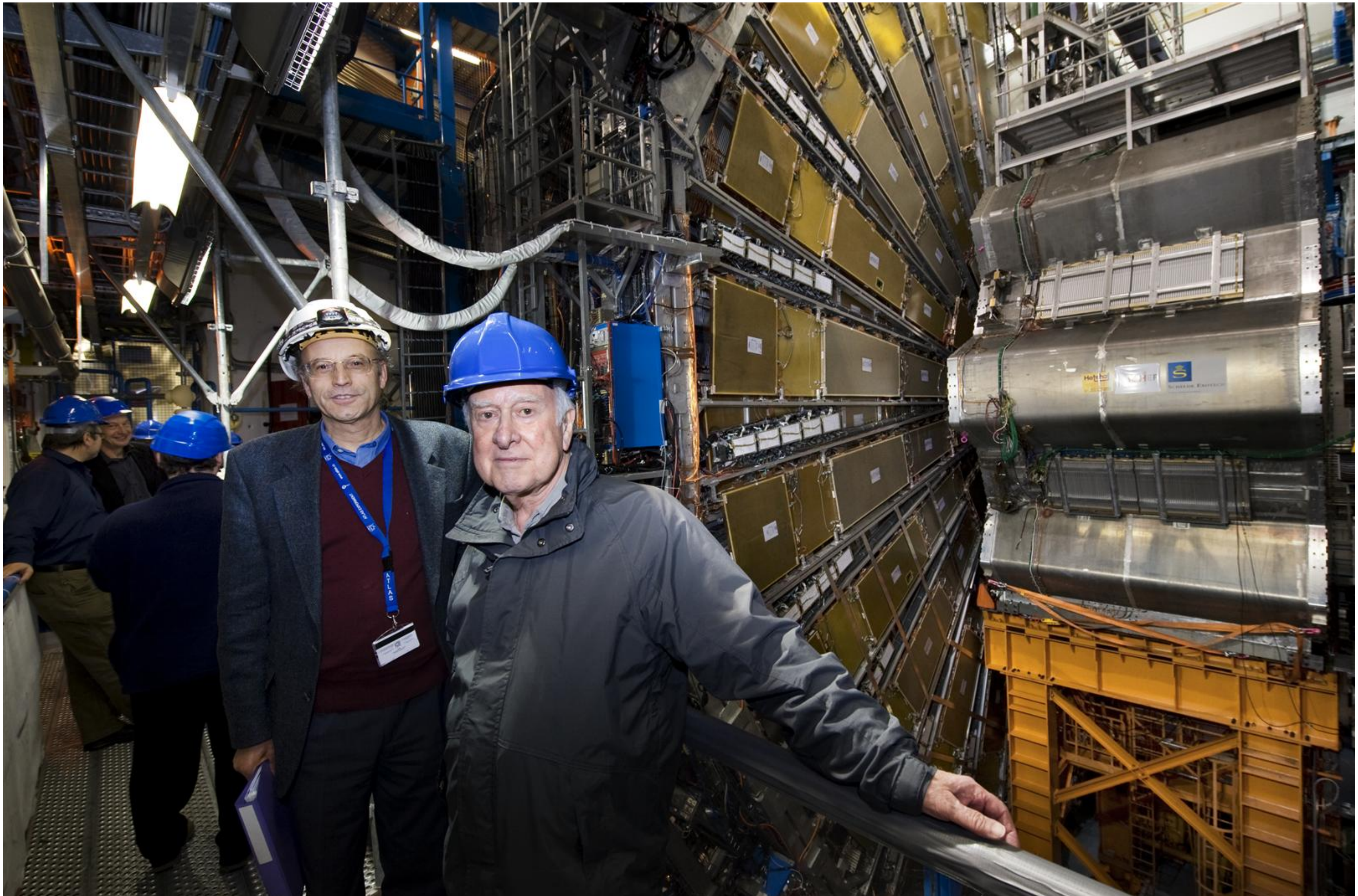
Calorimeters

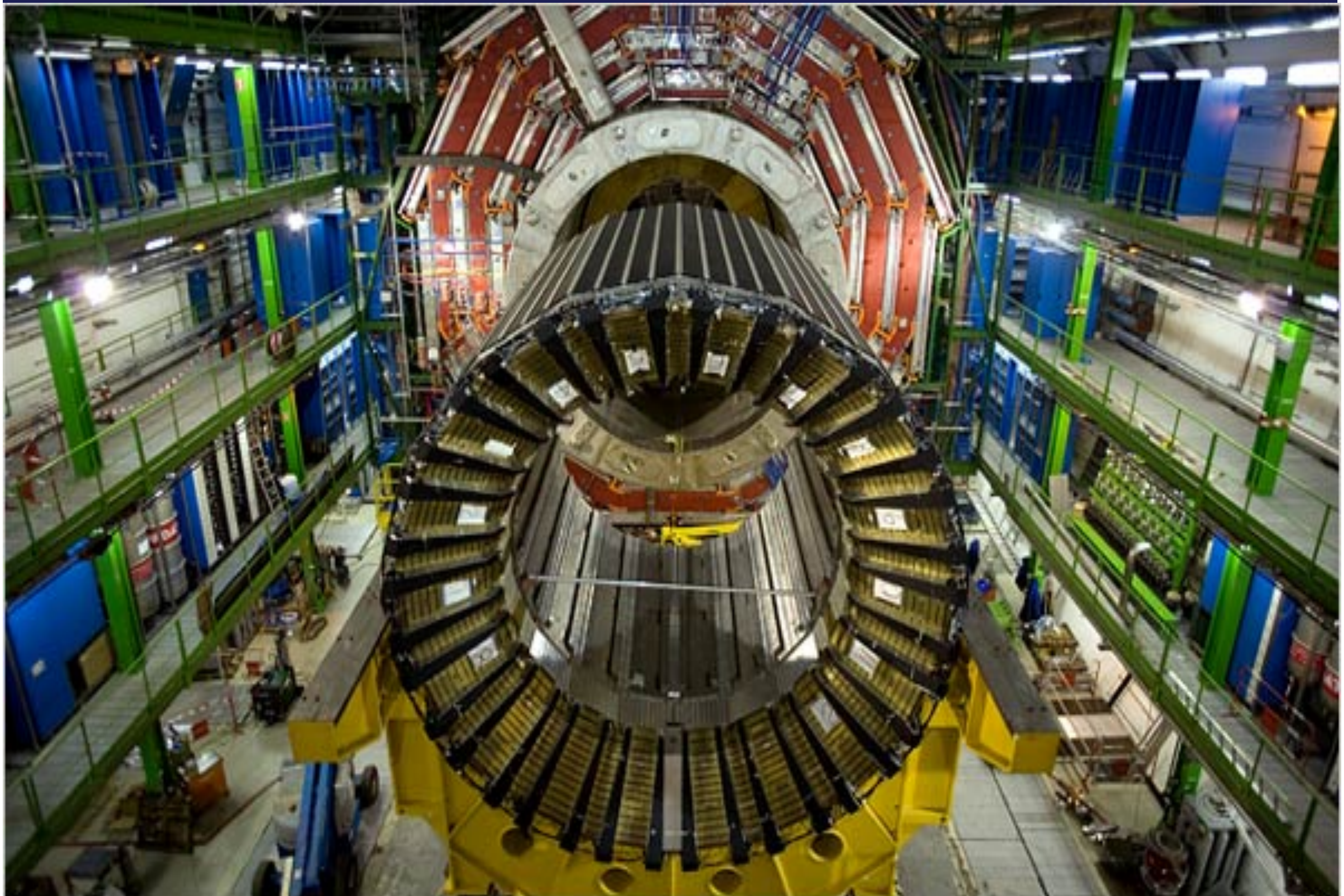


- Measure energy and position of electrically charged and neutral particles
  - Electrons and photons
  - Hadrons (protons, pions,…)



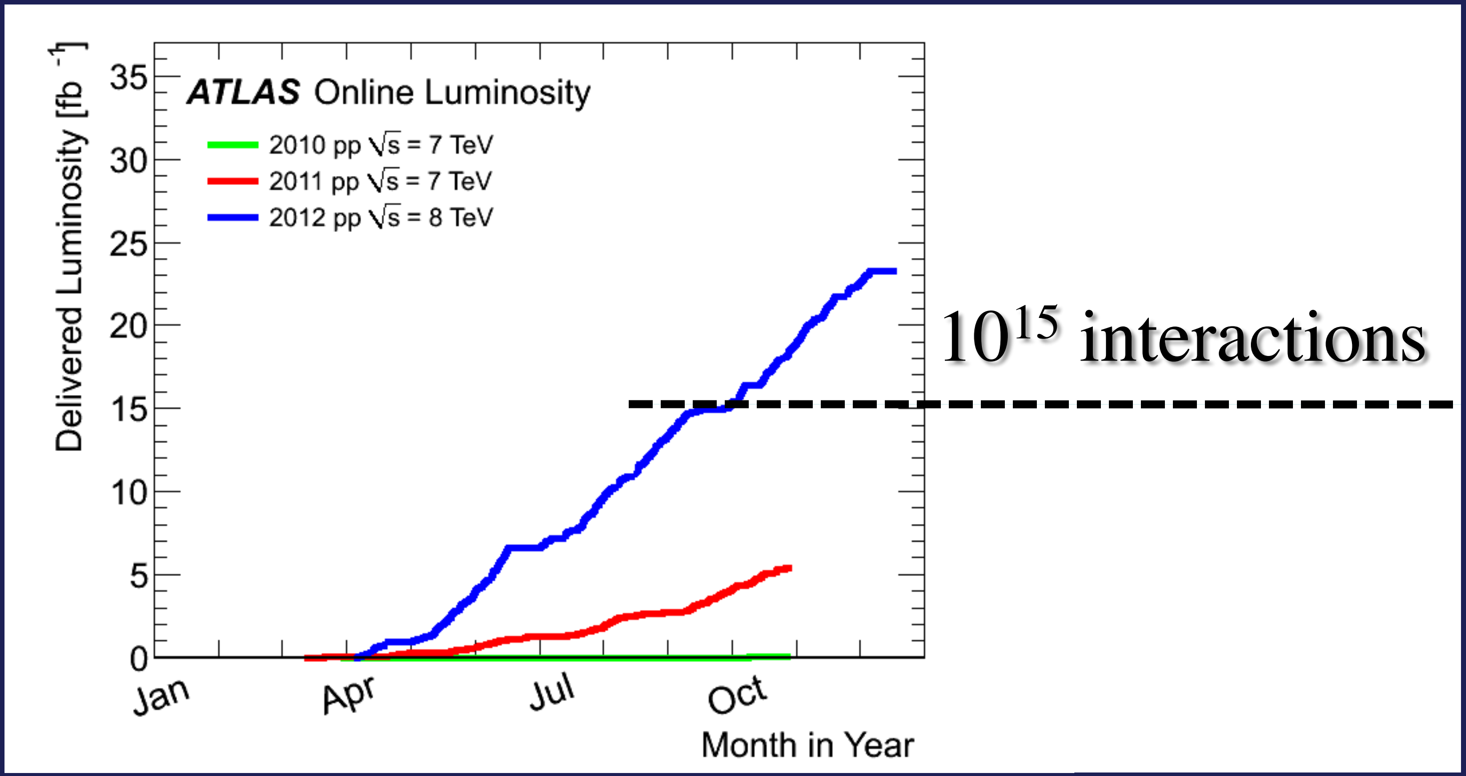






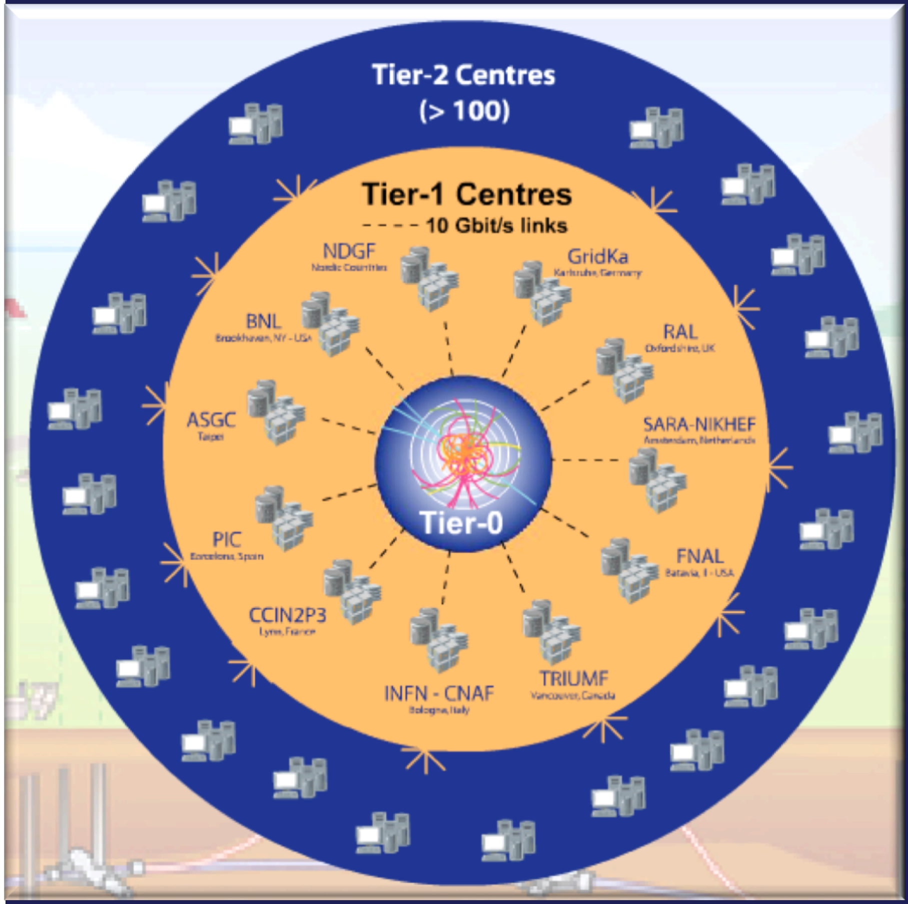
November 23rd, 2009: first pp collision!

LHC Data Taking: 2010-2012



- 24/7 operation typically from March – October each year
- Rate of interactions:
  - About 1 billion interactions per second
  - Fast "trigger" decision => record about 400 events/second

Worldwide LHC Computing Grid



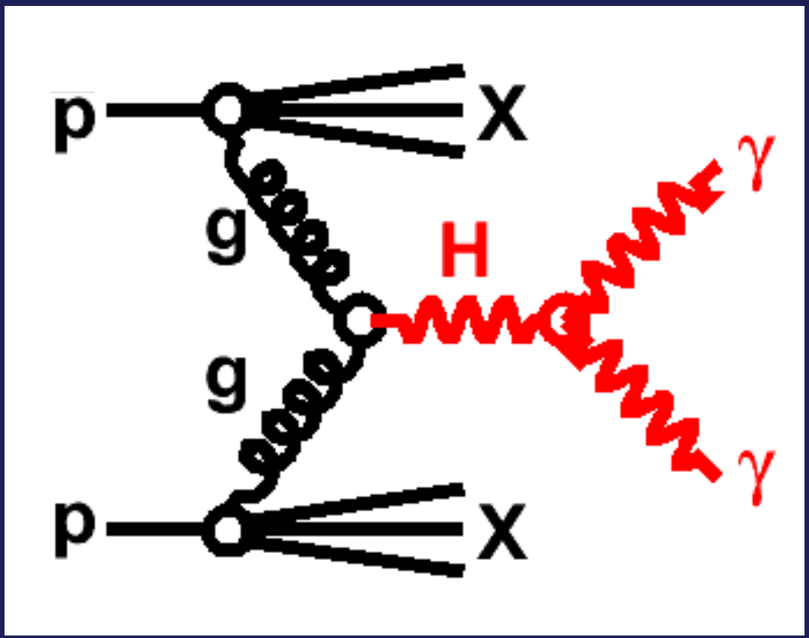
- Huge data volumes
  - 600 MB/s
  - 5,000 TB/year
- Huge CPU requirements:
  - 15 s/event

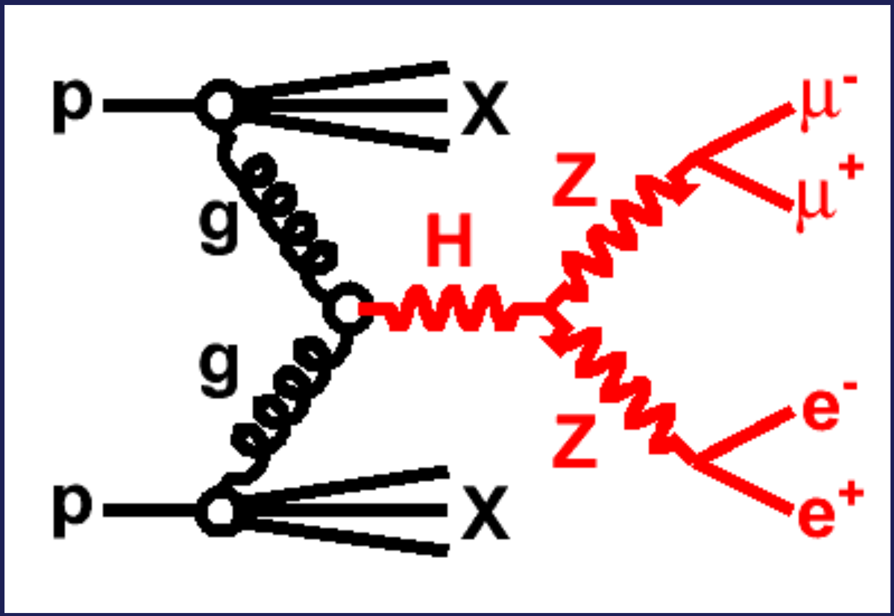
Data stored and analyzed on world-wide LHC computing grid:

11 clouds across the globe

The Higgs Boson Search

Production and Decay of a Higgs Boson

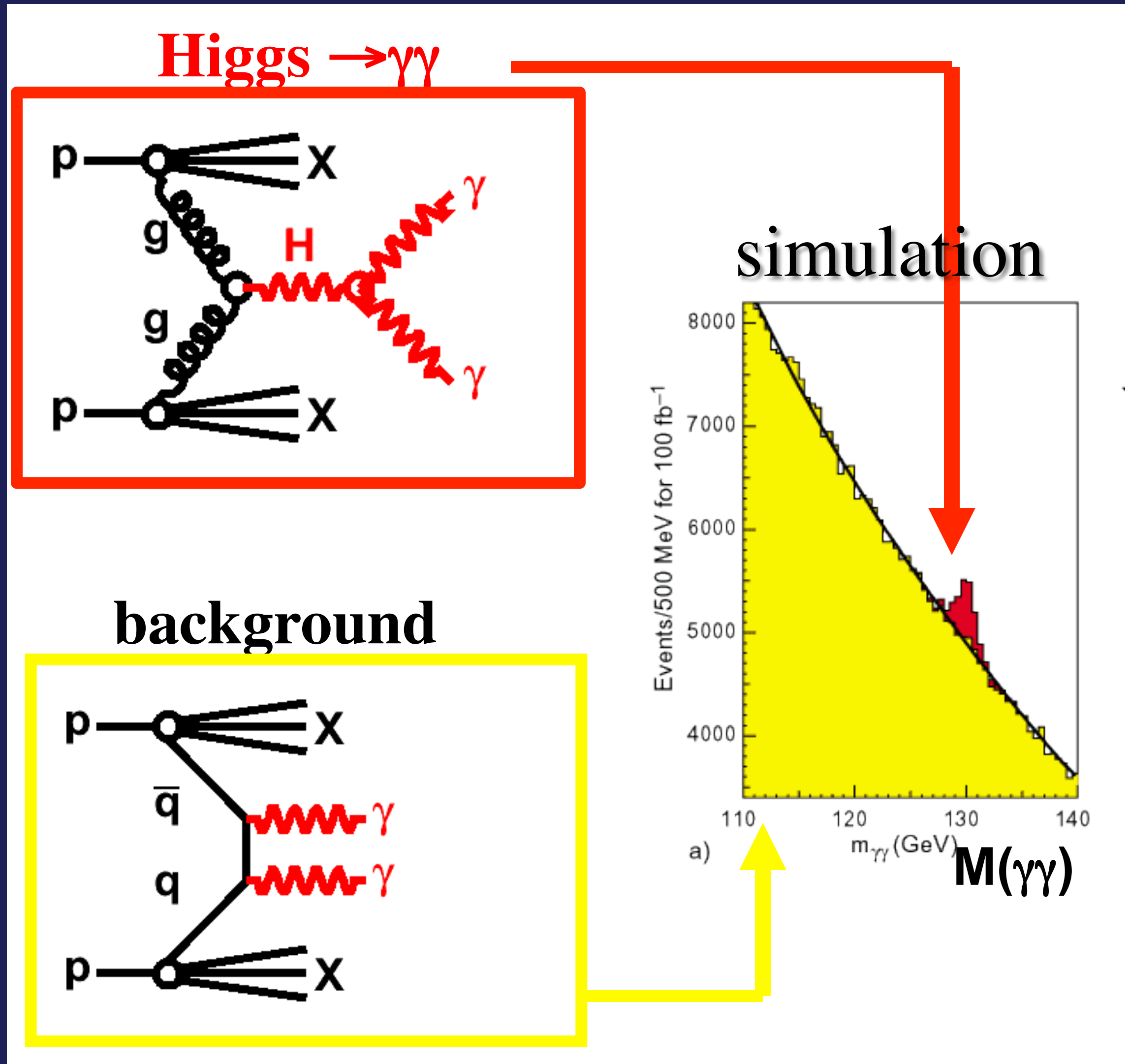




- Higgs boson is unstable and decays very quickly
  - 0.2% decay into **two photons**
  - 0.014% decay to **4 electrons or muons**
  - 99.8% of decays are harder to observe
    - also analyzed and important but will not explain here

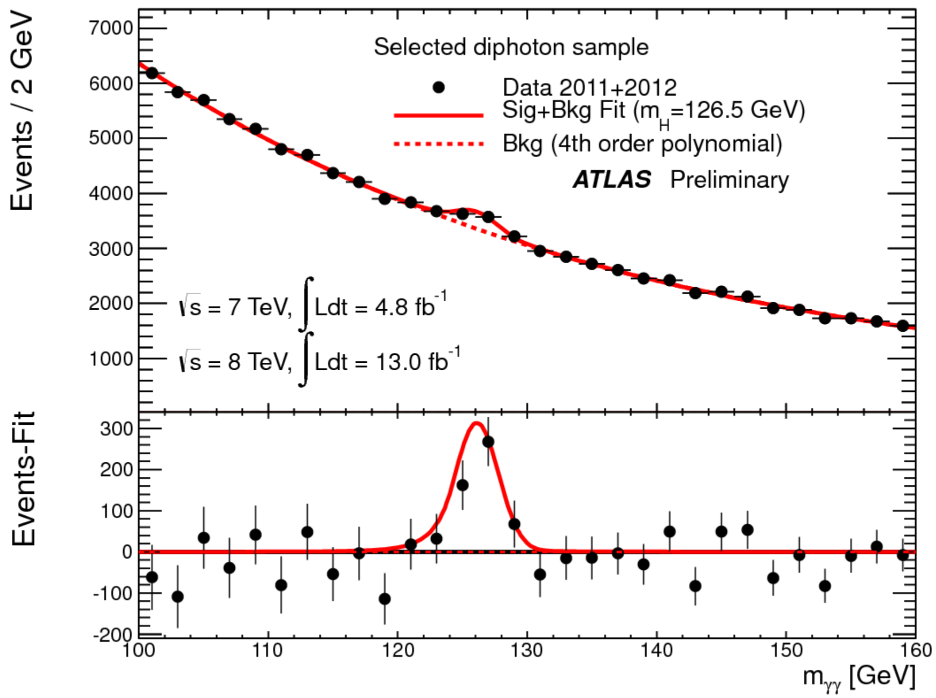
Finding the Higgs Boson (with photons)

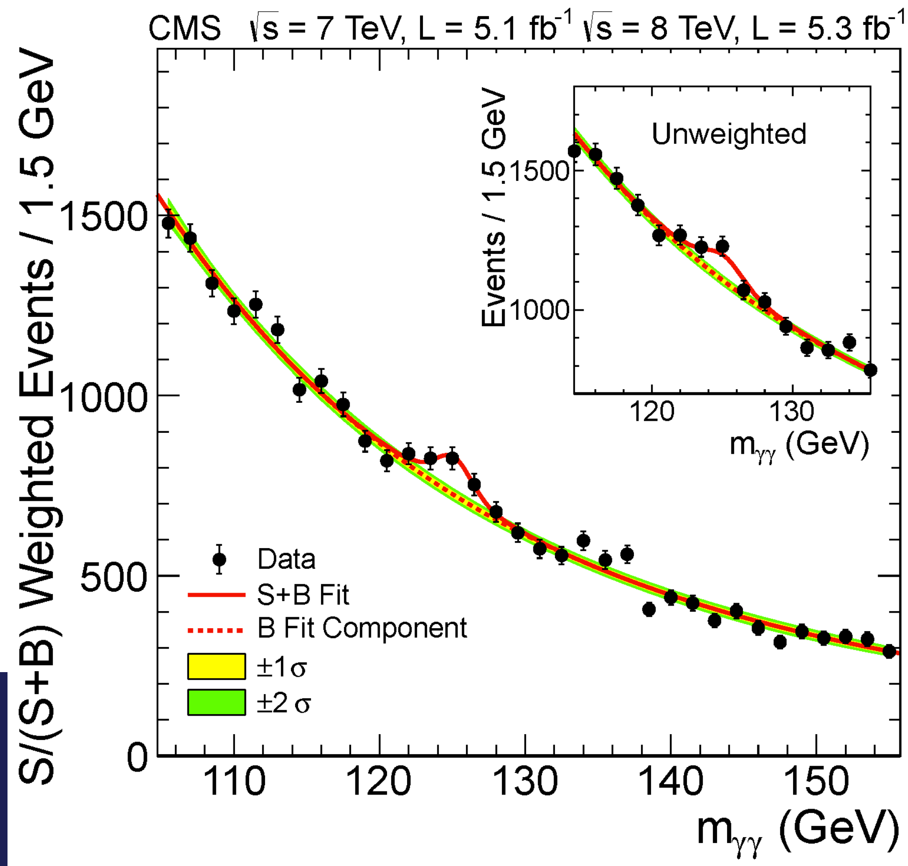
- Higgs boson decays to two high energy photons
  - Higgs mass determined from energies and angles of photons
- Background process looks identical
  - But creates no peak!



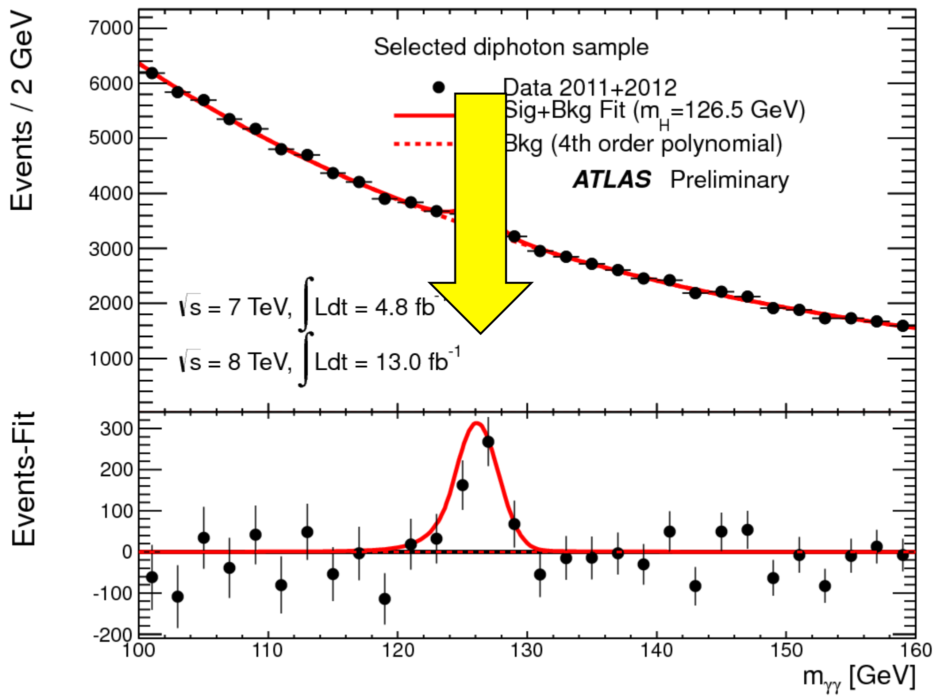
$$M_{Higgs} \approx M(\gamma\gamma) = 2\, E_1\, E_2\, (1-\cos\alpha)$$

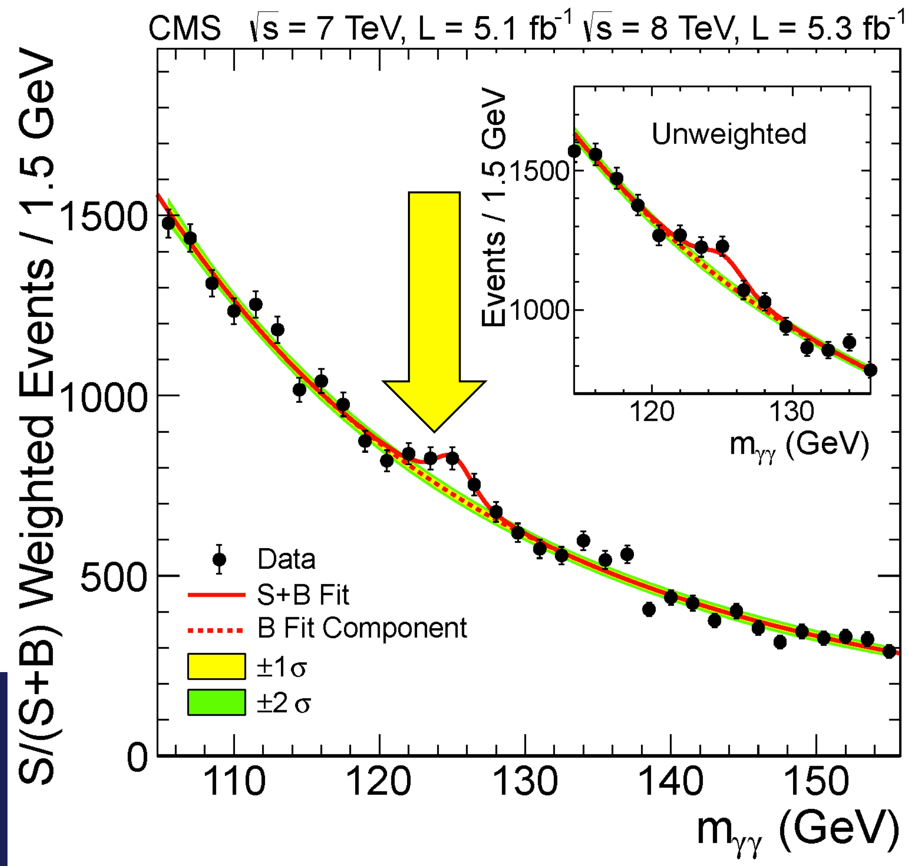
Diphoton Mass Distributions



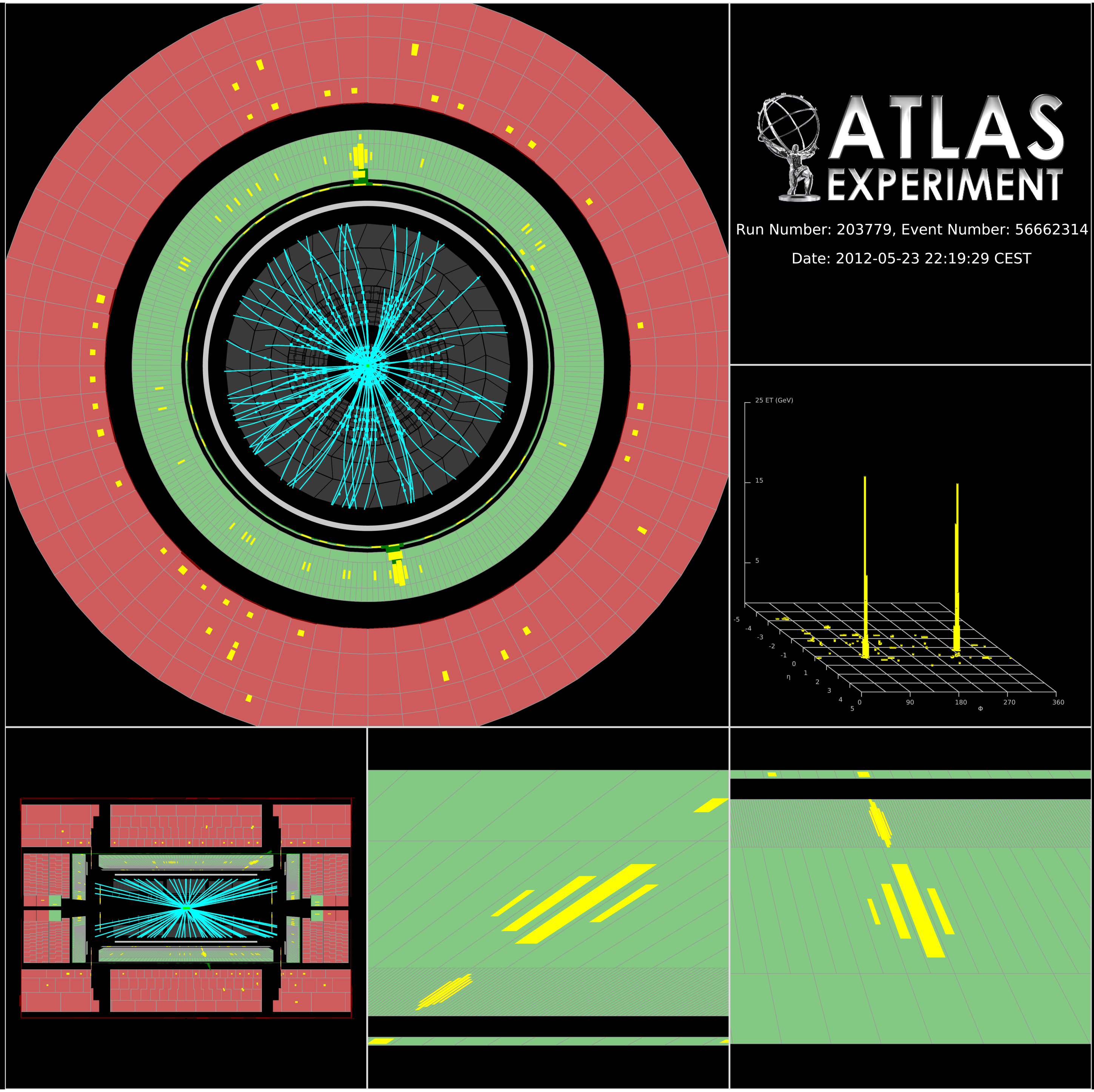


Diphoton Mass Distributions

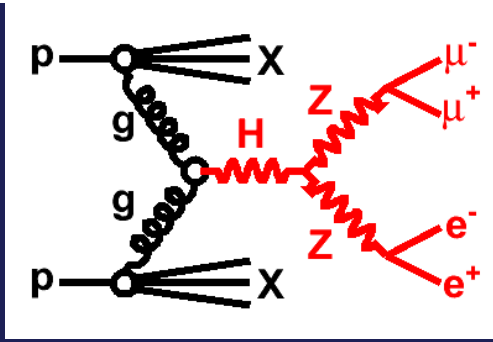


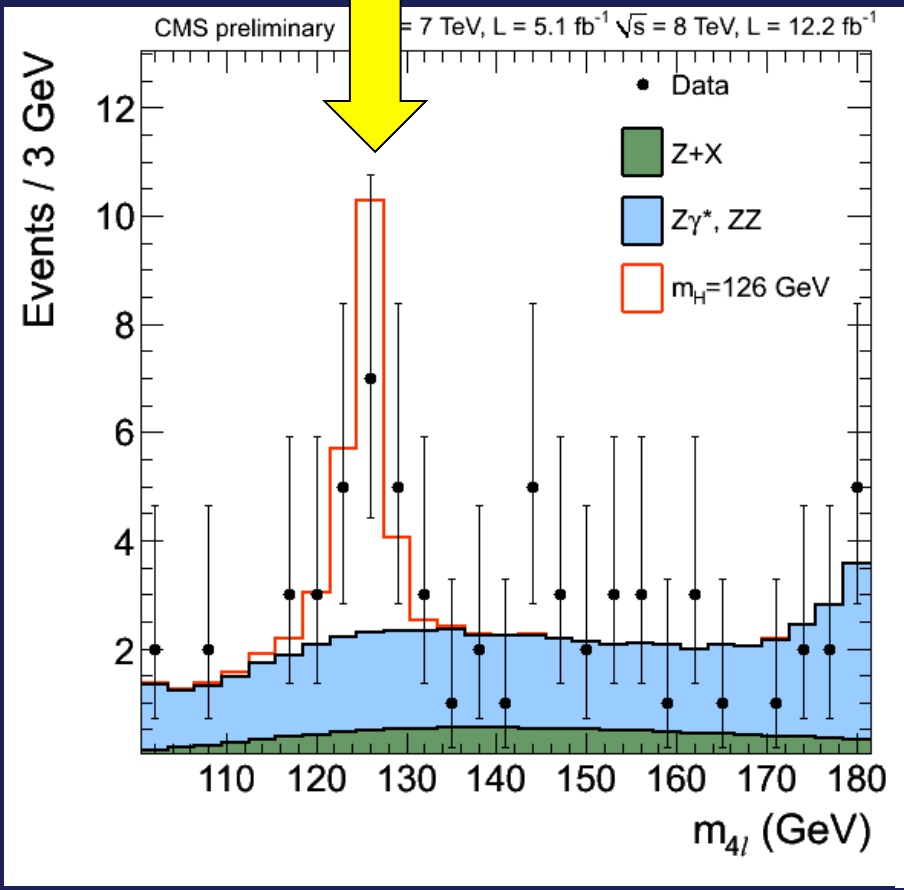


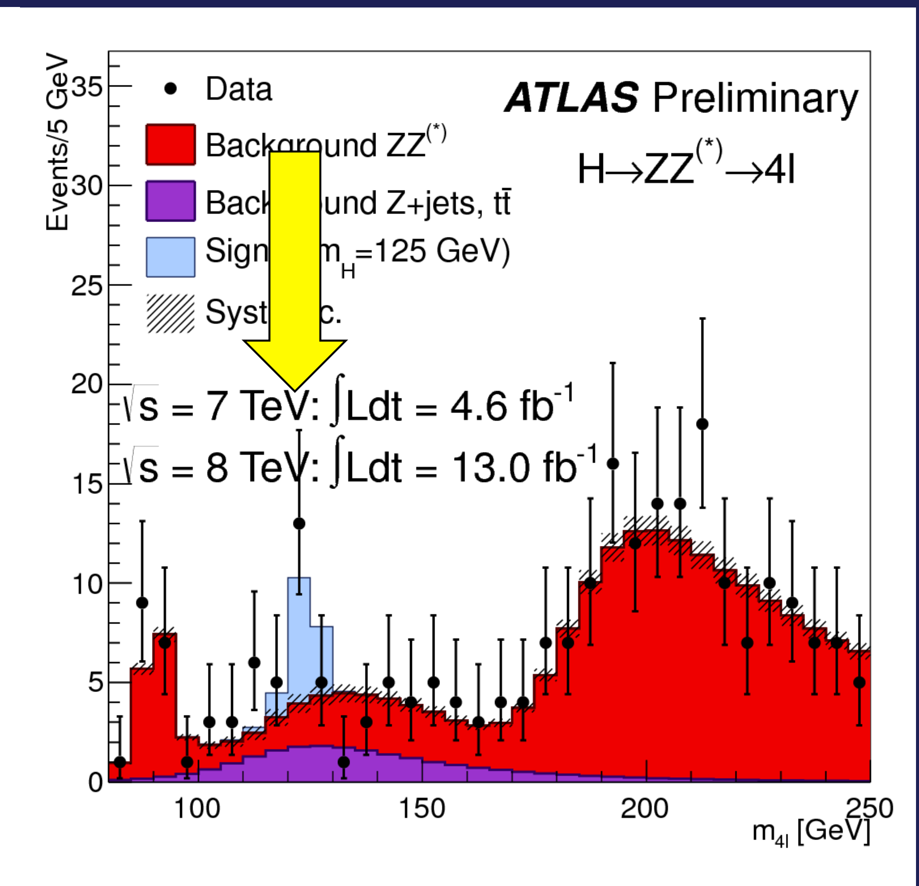
Both experiments see peak at ~126 GeV


ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
η
Φ
0
90
180
270
360

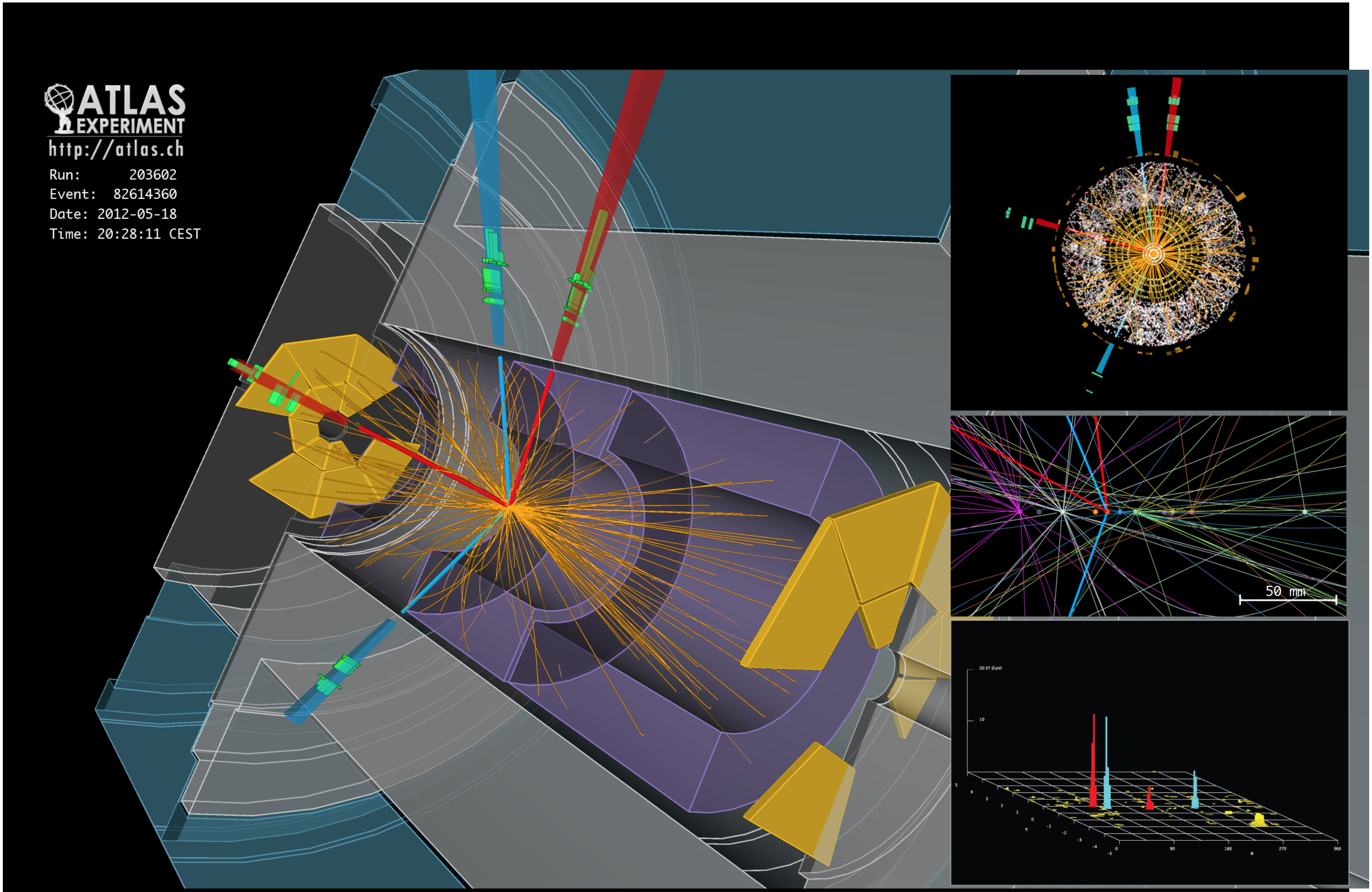
Higgs boson decaying to two Z bosons



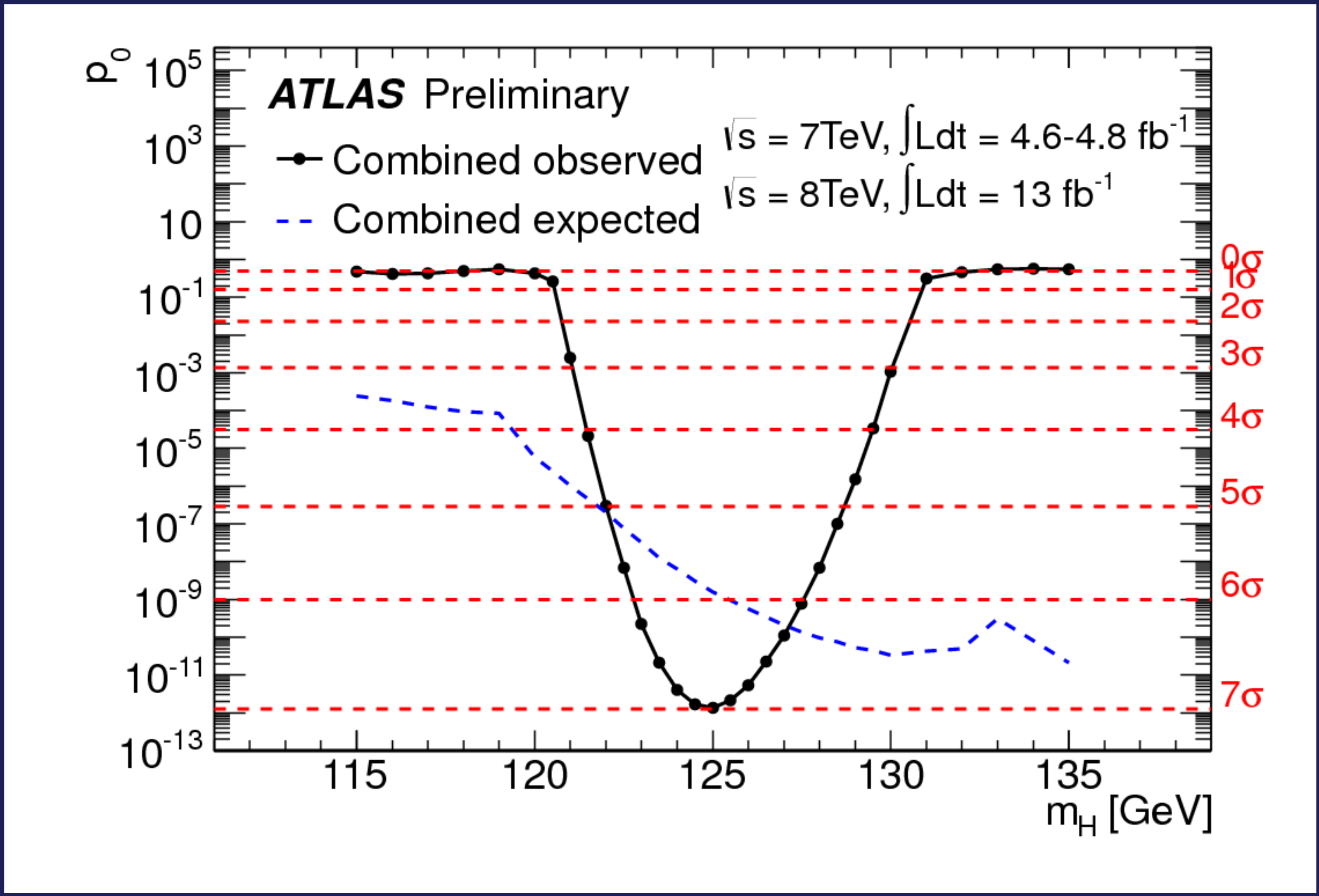




Both experiments see peak at ~126 GeV


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

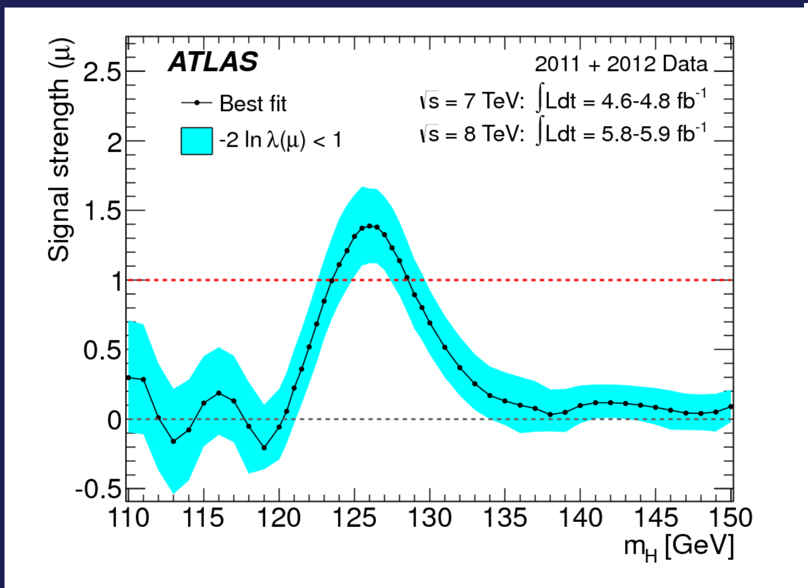
Probability of statistical fluctuation

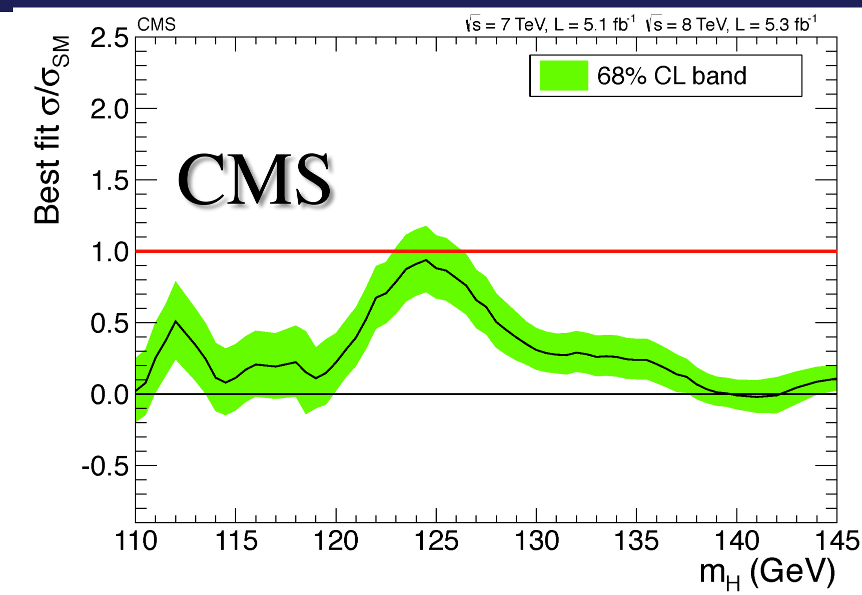


Probability of statistical fluke less than one in 100 billion

Discovery of a New Particle!

- Properties similar to those of Higgs boson
  - Signal strength consistent with expectation





  - Mass consistent between the two experiments:
    - ATLAS: **m=125.2 ± 0.7 GeV**
    - CMS: **m=125.8 ± 0.6 GeV**

Conclusions

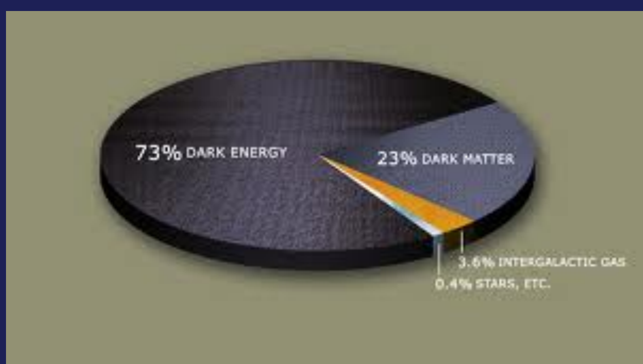
Fabiola Gianotti, ATLAS spokesperson

Peter Higgs

- **1964**: Higgs boson first thought of
  - solves how fundamental particles get mass
- **1992**: ATLAS and CMS collaborations founded
- **2012**: New particle observed consistent with Higgs boson

Outlook

- Many puzzles remain in Standard Model
  - Many other analyses ongoing in parallel at LHC
    - e.g. searches for Dark Matter particles
      - complementary to searches going on at LUX experiment here at SURF in the former Homestake mine



- LHC will have a 2-year break to do repairs
- 2015: nearly double the energy (8 => 13 TeV)
  - Great chance to discover other new particles
  - Further study Higgs boson
    - Is it fully consistent with our Standard Model?

More Information

- Information, explanations, movies, images …
  - http://public.web.cern.ch
  - http://atlas.ch
  - http://cmsinfo.cern.ch/outreach

Backup Slides

LHC milestones

- March 2007: last dipole magnet installed
- September 2008: first beam but major accident prevents LHC startup in 2008
- Nov. 2009: first collisions at injection energy (900 GeV)
- March 2010: first collisions at 7 TeV
  - 3.5 time higher energy than Tevatron
- End of 2010: $L=40\ pb^{-1}$ of data recorded
  - Sufficient to make many tests of Standard Model and to test supersymmetry beyond Tevatron
  - Not enough to test the Higgs
- End of 2011: $L=5\ fb^{-1}$ of data recorded
  - nearly 100 times more than 2010
  - Sufficient to probe Higgs boson over much of the mass range

Supersymmetry

Symmetry between
fermions (matter) and bosons (forces)
"Undiscovered new symmetry"

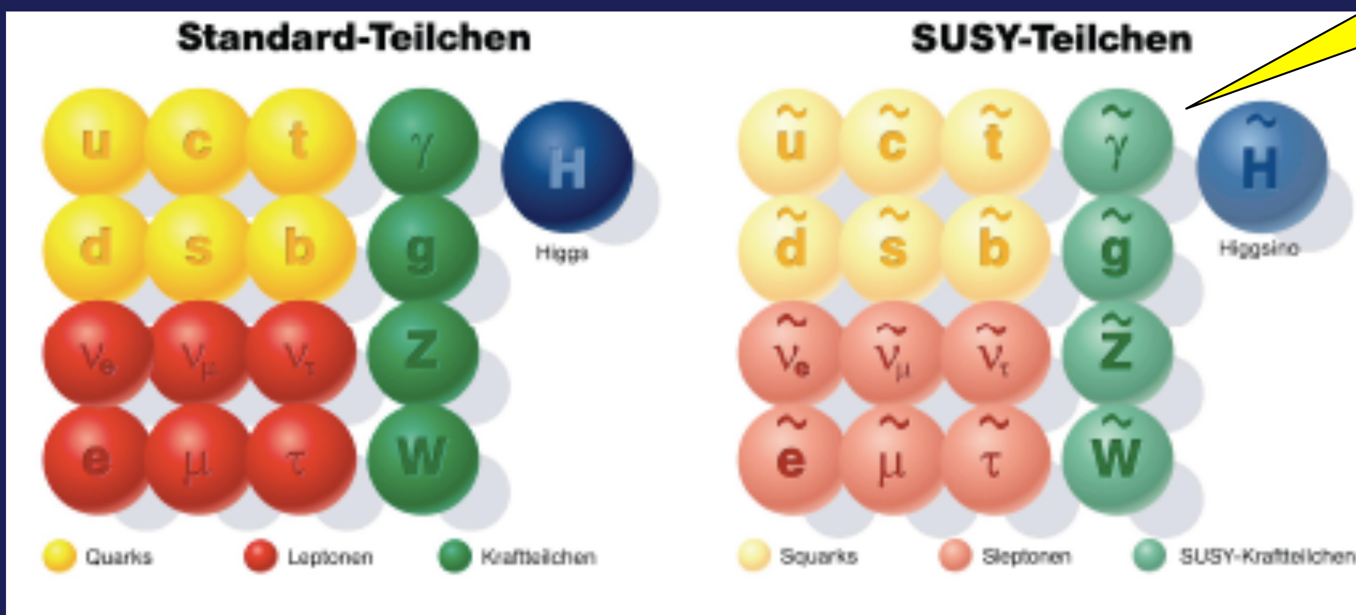
e $\swarrow \searrow$ e+ e-

superparticle $\swarrow \searrow$ e $\tilde{e}$

spin 1/2 spin 0

$M_e \neq M_{\tilde{e}}$

Dark Matter candidate: "photino"



What is the Higgs Boson Mass?

Isidori, Rychkov, Strumia, Tetradis '08